

This Page Is Inserted by IFW Operations
and is not a part of the Official Record

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images may include (but are not limited to):

- BLACK BORDERS
- TEXT CUT OFF AT TOP, BOTTOM OR SIDES
- FADED TEXT
- ILLEGIBLE TEXT
- SKEWED/SLANTED IMAGES
- COLORED PHOTOS
- BLACK OR VERY BLACK AND WHITE DARK PHOTOS
- GRAY SCALE DOCUMENTS

IMAGES ARE BEST AVAILABLE COPY.

**As rescanning documents *will not* correct images,
please do not report the images to the
Image Problems Mailbox.**



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁶: H01L 33/00, 51/20	A1	(11) International Publication Number: WO 97/47050 (43) International Publication Date: 11 December 1997 (11.12.97)
(21) International Application Number: PCT/IB96/00557 (22) International Filing Date: 5 June 1996 (05.06.96) (71) Applicant (for all designated States except US): INTERNATIONAL BUSINESS MACHINES CORPORATION [US/US]; Old Orchard Road, Armonk, NY 10504 (US). (72) Inventors; and (75) Inventors/Applicants (for US only): RIESS, Walter [DE/CH]; Gstalderstrasse 3, CH-8134 Adliswil (CH). STRITE, Samuel, Clagett [US/CH]; Hornhaldenstrasse 1, CH-8802 Kilchberg (CH). (74) Agent: HEUSCH, Christian; International Business Machines Corporation, Säumerstrasse 4, CH-8803 Rüschlikon (CH).		(81) Designated States: JP, KR, US, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published <i>With international search report.</i> <i>With amended claims.</i>
(54) Title: NON-DEGENERATE WIDE BANDGAP SEMICONDUCTORS AS INJECTION LAYERS AND/OR CONTACT ELECTRODES FOR ORGANIC ELECTROLUMINESCENT DEVICES		
(57) Abstract An organic light emitting device is provided which comprises a substrate (60), an anode contact electrode (64), a cathode contact electrode (61), and an organic region (62, 63) in which electroluminescence takes place if a voltage is applied between said anode (64) and cathode (61). At least one of said electrodes (61, 64) comprises a non-degenerate wide bandgap semiconductor.		

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece	ML	Mali	TR	Turkey
BG	Bulgaria	HU	Hungary	MN	Mongolia	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MR	Mauritania	UA	Ukraine
BR	Brazil	IL	Israel	MW	Malawi	UG	Uganda
BY	Belarus	IS	Iceland	MX	Mexico	US	United States of America
CA	Canada	IT	Italy	NE	Niger	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NL	Netherlands	VN	Viet Nam
CG	Congo	KE	Kenya	NO	Norway	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NZ	New Zealand	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	PL	Poland		
CM	Cameroon	KR	Republic of Korea	PT	Portugal		
CN	China	KZ	Kazakhstan	RO	Romania		
CU	Cuba	LC	Saint Lucia	RU	Russian Federation		
CZ	Czech Republic	LI	Liechtenstein	SD	Sudan		
DE	Germany	LK	Sri Lanka	SE	Sweden		
DK	Denmark	LR	Liberia	SG	Singapore		
EE	Estonia						

DESCRIPTION**Non-Degenerate****Wide Bandgap Semiconductors as Injection Layers and/or
Contact Electrodes for Organic Electroluminescent Devices****TECHNICAL FIELD**

The present invention pertains to organic electroluminescent devices, such as discrete light emitting devices, arrays, displays, and in particular to injection layers and contact electrodes suited for such devices. It furthermore relates to a method for making the same.

BACKGROUND OF THE INVENTION

Organic electroluminescence (EL) has been studied extensively because of its possible applications in discrete light emitting devices, arrays and displays. Organic materials investigated so far can potentially replace conventional inorganic materials in many applications and enable wholly new applications. The ease of fabrication and extremely high degrees of freedom in organic EL device synthesis promises even more efficient and durable materials in the near future which can capitalize on further improvements in device architecture.

Organic EL at low efficiency was observed many years ago in metal/organic/metal structures as, for example, reported in Pope et al., Journal Chem. Phys., Vol. 38, 1963, pp. 2024, and in "Recombination Radiation in Anthracene Crystals", Helfrich et al., Physical Review Letters, Vol. 14, No. 7, 1965, pp. 229-231. Recent developments have been spurred largely by two reports of high efficiency organic EL. These are C.W. Tang et al., "Organic electroluminescent diodes", Applied Physics Letters, Vol. 51,

1 No. 12, 1987, pp. 913-915, and by a group from Cambridge University in
Burroughs et al., Nature, Vol. 347, 1990, pp. 539. Tang et al. made
two-layer organic light emitting devices using vacuum deposited molecular
dye compounds, while Burroughs used spin coated
5 poly(p-phenylenevinylene) (PPV), a polymer.

The advances described by Tang and in subsequent work by the Cambridge
group, for example in "Efficient LEDs based on polymers with high electron
affinities", N. Greenham et al., Nature, Vol. 365, 1993, pp. 628-630, were
10 achieved mainly through improvements in the design of EL devices derived
from the selection of appropriate organic multilayers and contact metals.

Organic EL light emitting devices (OLEDs) function much like inorganic
LEDs, except that light is commonly extracted through a transparent
15 electrode deposited on a transparent glass substrate. The simplest possible
structure, schematically illustrated in Figure 1A, consists of an organic
emission layer 10 sandwiched between two electrodes 11 and 12 which
inject electrons (e^-) and holes (h^+), respectively. Such a structure has been
described in the above mentioned paper of Burroughs et al., for example.
20 The electrons and holes meet in the organic layer 10 and recombine
producing light. It has been shown in many laboratories, see for example:
"Conjugated polymer electroluminescence", D. D. C. Bradley, Synthetic
Metals, Vol. 54, 1993, pp. 401-405. "The effect of a metal electrode on the
electroluminescence of Poly(p-phenylvinylene)", J. Peng et al., Japanese
25 Journal of Applied Physics, Vol. 35, No. 3A, 1996, pp. L317-L319, and
"Carrier tunneling and device characteristics in polymer LEDs", I. D. Parker,
Journal of Applied Physics, Vol. 75, No. 3, 1994, pp. 1656-1666, that
improved performance can be achieved when the electrode materials are
chosen to match the respective molecular orbitals of the organic material
30 forming the organic layer 10. Such an improved structure is shown in
Figure 1B. By choosing the optimized electrode materials 13 and 14, the
energy barriers to injection of carriers are reduced, as illustrated. Still, such
simple structures perform poorly because little stops electrons from

1 traversing the organic layer 10 and reaching the anode 14, or the hole from
reaching the cathode 13.

Figure 2A illustrates a device with a large electron barrier 16 such that only
5 few electrons are injected, leaving the holes no option but to recombine in
the cathode 15.

A second problem, illustrated in Figure 2B, is that the mobilities of
electrons and holes in most known organic materials, especially conductive
10 ones, differ strongly. Figure 2B illustrates an example where holes injected
from the anode 18 quickly traverse the organic layer 19, while the injected
electrons move much slower, resulting in recombination near the cathode
17. If the electron mobility in the organic layer 19 were larger than the
holes', recombination would occur near the anode 18. Recombination near
15 a metal contact is strongly quenched by the contact which limits the
efficiency of such flawed devices.

Tang, as shown in Figure 3, separated electron and hole transport functions
between separate organic layers, an electron transport layer 20 (ETL) and a
20 hole transport layer (HTL) 21, mainly to overcome the problems described
above. In "Electroluminescence of doped organic thin films", C.W. Tang et
al., Journal of Applied Physics, Vol. 65, No. 9, 1989, pp. 3610-3616, it is
described that higher carrier mobility was achieved in the two-layer design,
which led to reduced device series resistance enabling equal light output at
25 lower operating voltage. The contact metals 22, 23 could be chosen
individually to match to the ETL 20 and HTL 21 molecular orbitals,
respectively, while recombination occurred at the interface 24 between the
organic layers 20 and 21, far from either electrode 22, 23. As electrodes,
Tang used a MgAg alloy cathode and transparent Indium-Tin-Oxide (ITO) as
30 the anode. Egusa et al. In "Carrier injection characteristics of organic
electroluminescent devices", Japanese Journal of Applied Physics, Vol. 33,
No. 5A, 1994, pp. 2741-2745 have shown experimentally that the proper
selection of the organic multilayer can lead to a blocking of both electrons

1 and holes at an organic interface remote from either electrode. This effect
is illustrated by the structure of Figure 3 which blocks electrons from
entering the HTL 21 and vice versa by a clever choice of HTL and ETL
materials. This feature eliminates non-radiative recombination at the metal
5 contacts as illustrated in Figure 1A and also promotes a high density of
electrons and holes in the same volume leading to enhanced radiative
recombination.

The heterojunction molecular orbital energy alignment illustrated in
10 Figure 3 actually reflects a trend in preferred OLED materials which is
beneficial to device design (and to the present invention as will be
discussed later). The trend is that materials which tend to transport
electrons with high mobility 20 do so, in part, because their LUMOs lie at
lower energy. Similarly, good hole conductive properties go hand-in-hand
15 with HOMOs lying at higher energy. These facts make it more probable that
a heterojunction formed between an electron and hole transporting organic
layer will block the injection of one or both carriers at the interface due to
the energy discontinuities of the respective molecular orbitals. The blocking
effect localizes the carriers far from the quenching electrodes where they
20 can recombine most efficiently.

Two technical terms are commonly used which describe the positioning of
the two relevant organic molecular orbitals: the highest occupied molecular
orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) of
25 organic materials, or in the case of semiconductors, the positioning of their
respective counterparts, the valence bands (VB) and conduction bands (CB).
These terms in our treatment all have units of lower energies than a free
electron, which reflects the fact that they are bound, and energy is required
to remove electrons from nearly all known materials. For convenience, we
30 arbitrarily define a free electron to have zero energy, and therefore speak in
terms of the above quantities having negative energy values with respect to
the free electron (or vacuum) state.

1 The first of these terms is the work function, which describes how much
energy is required to 'pull' the most weakly bound electron out of the
material, i.e. to make it a free electron. In a metal or degenerate
semiconductor (i.e. a semiconductor characterized by an extremely high
5 free carrier concentration), the work function is identical to another quantity
called the Fermi energy level. Metals or degenerate semiconductors have
partially filled bands which are responsible for their large number of free
conduction carriers. The Fermi energy level is the energy to which the
highest energy band is filled, because it is these highest energy electrons
10 which are the easiest to liberate energetically.

In the following, whenever we refer to an energy level, be it the work
function, HOMO or LUMO, conduction band or valence band, or Fermi
energy, it is in the above context.

15

With multilayer device architectures now well understood and commonly
used, the major performance limitation of OLEDs is the lack of ideal contact
electrodes. The main figure of merit for electrode materials known in the art
is the position in energy of the electrode Fermi level relative to the energy
20 of the organic molecular orbital into which it must inject (see Bradley and
Parker above for detailed discussion). In some applications it is also
desirable for the electrode material to be either transparent or highly
reflective. The electrode should also be chemically inert and capable of
forming a dense uniform film to effectively encapsulate the OLED. It is also
25 desirable that the electrode not strongly quench organic EL.

No cathode material has yet been identified which is transparent,
conductive, chemically stable, and a good electron injector for OLEDs.
Good electron transporting organic materials have their lowest unoccupied
30 molecular orbitals (LUMO) matched in energy only with low work function
metals. A low work function in a metal is tantamount to high chemical
reactivity. While, e.g., Ca has its work function well matched in energy to an
Alq3 (tris(8-hydroxyquinoline aluminum)) organic electron transport layer

- 1 LUMO, a Ca cathode survives intact only a short time in air, leading to rapid
device degradation. It is also likely that such highly reactive metals undergo
a chemical reaction with the nearby organic materials which also could have
negative effects on device performance. Such a mechanism has been
5 proposed by Parker in the above cited reference to explain why Sm or Yb
cathode OLEDs have poorer performance than Ca cathode OLEDs despite
the lower work function of Sm and Yb compared to Ca. A low work function
cathode metal approach requires careful handling of the device to avoid
contamination of the cathode metal, and immediate, high quality
10 encapsulation of the device if operation in a normal atmosphere is desired.
Even well encapsulated low work function metal contacts are subject to
degradation resulting from naturally evolved gases, impurities, solvents
from the organic LED materials.
- 15 On the other hand, the choice of a stable metal having a higher work
function, e.g. Al, dictates that the device can only be operated at high
voltages. High voltage is necessary because electron injection from Al into,
e.g., the Alq3 LUMO is field assisted. The high operating voltage reduces
device efficiency due to increased ohmic losses. In addition, the higher
20 electrical fields present at increased voltages also are likely to degrade the
device materials more rapidly by driving interdiffusion or exciting parasitic
chemical reactions or recombination processes. Al contacts, of lesser
reactivity compared to Mg or Ca, have still been observed to degrade
during OLED operation, see e.g. L. M. Do et al., "Observation of
25 degradation processes of Al electrodes in organic EL devices by
electroluminescence microscopy, atomic force microscopy, and Auger
electron microscopy", Journal of Applied Physics, Vol. 76, No. 9, 1994,
pp. 5118-5121.
- 30 Many approaches have been attempted in order to solve the problem of
cathode electrode instability, degradation and high injection voltage. A
common approach is the use of a low work function metal subsequently
buried under a thicker metal coating. In this case, pinholes in the metal still

1 provide ample pathways for oxygen and water to reach the reactive metal
below, as is described in: Y. Salo et al., "Stability of organic
electroluminescent diodes", *Molecular Crystals and Liquid Crystals*,
Vol. 253, 1994, pp. 143-150 and J. Kido et al., "Bright organic
5 electroluminescent devices with double-layer cathode", *IEEE Transactions*
on Electron Devices, Vol. 40, No. 7, 1993, pp. 1342-1344. Furthermore, such
contacts are degraded by evolved gases from the OLED constituent
materials. The overall lifetime of OLEDs using this approach is limited and
extensive encapsulation is required.

10

Much less attention has been paid to the optimization of the anode contact,
since ITO or Au anodes generally outperform the cathode contact. However,
if the anode electrode could be improved, it would have a similarly positive
effect on device performance and reliability as improved cathodes.

15

Indium-tin-oxide has been the anode of choice for years. Its major
advantage is that it is a transparent conductor which also has a large work
function (roughly 4.9 eV), and is therefore well suited for the formation of a
transparent anode on glass. However, ITO is known to have a barrier to hole
20 injection into preferred organic HTL materials. Parker showed that, by
replacing ITO with Au, which has a larger work function, in an identical
OLED structure, the device efficiency is doubled due to the elimination of
the ITO/organic hole injection barrier. ITO is also responsible for device
degradation as a result of In diffusion emanating from the ITO into the OLED
25 which can eventually cause short circuiting. In diffusion from ITO into PPV
was clearly identified in G. Sauer et al., "Characterization of polymeric LEDs
by SIMS depth profiling analysis," *Fresenius J. Analyt. Chem.*, in press. ITO
also acts as an reservoir of oxygen, which is detrimental to organic LED
materials when it diffuses from the ITO into the organic layers. This
30 problem has been elucidated in: J. C. Scott et al., "Degradation and failure
of MEH-PPV light-emitting diodes", *Journal of Applied Physics*, Vol. 79,
1996, pp. 2745 -2751. ITO is a polycrystalline material in the form
commonly used for OLEDs. The abundance of grain boundaries provides

1 ample pathways for contaminant diffusion through the ITO. Finally, ITO also
is a reservoir of oxygen which is known to have a detrimental effect on
common organic materials. Despite all of these known problems related to
ITO anodes, they are still favored in the art because no other transparent
5 electrode material of similar or better quality is yet known in the art. At least
one transparent electrode is necessary for a practical OLED, since the light
must be efficiently extracted to be useful.

While Au has a large (5.2 eV) work function, long-lived OLED devices cannot
10 be made using Au cathodes because of the very high diffusivity of Au in
organic materials. Like In and O diffusion out of ITO, only worse, Au from
the contact diffuses through the OLED and eventually short circuits the
device. In addition, Au is not a practical anode material for most
architectures because it is not transparent. For the lack of a transparent
15 cathode material, the anode must be the transparent contact for present day
OLEDs.

Other semiconductors besides ITO have been tried as OLED electrodes. 1.
D. Parker and H. H. Kim, "Fabrication of polymer light-emitting diodes using
20 doped silicon substrates", Applied Physics Letters, Vol. 64, No. 14, 1994,
pp. 1774-1776, showed that, depending on the semiconductor doping, the
Si/SiO₂ is capable of either hole or electron injection into organic thin films.
This work applied the Si semiconductor electrode towards majority carrier
injection, i.e. n-type Si for electron injection and p-type for hole injection.
25 Si electrodes had a large barrier to both electron and hole injection into
OLED materials. This is due to the small bandgap of Si and the moderate
positioning of the Si conduction and valence bands in energy. Si is also
absorbing to much of the visible spectrum, and represented no
improvement over conventional metals. Parker and Kim circumvented the
30 poor Si band energy positioning by adding a SiO₂ interlayer between the Si
contact and OLED. While the voltage drop across the SiO₂ insulator
permitted the Si bands to line up with their organic molecular orbital
counterpart, electrons were not directly injected, rather forced to tunnel

1 through the SiO₂ insulator. Such OLEDs had turn-on voltages of > 10 V, too
high for efficient device operation.

The lack of inert, stable, energetically matched, and transparent electrode
5 materials for low voltage, efficient and stable OLED operation remains a
major obstacle to OLED development.

Organic LEDs have great potential to outperform conventional inorganic
LEDs in many applications. One important advantage of OLEDs and devices
10 based thereon is the price since they can be deposited on large,
inexpensive glass substrates, or a wide range of other inexpensive
transparent, semitransparent or even opaque crystalline or non-crystalline
substrates at low temperature, rather than on expensive crystalline
substrates of limited area at comparatively higher growth temperatures (as
15 is the case for inorganic LEDs). The substrates may even be flexible
enabling pliant OLEDs and new types of displays. To date, the performance
of OLEDs and devices based thereon is inferior to inorganic ones for
several reasons:

- 20 1. High operating voltage: Organic devices require more voltage to inject
and transport the charge to the active region (emission layer) which in
turn lowers the power efficiency of such devices. High voltage results
from the need for high electric fields to inject carriers over energy
barriers at the electrode/organic interfaces, and from the low mobility of
25 the carriers in the organic transport layers (ETL and HTL) which leads to
a large ohmic voltage drop and power dissipation.
2. Low brightness: Today's OLEDs can produce nearly as many photons
per electron as common inorganic LEDs, i.e. their quantum efficiency is
30 good. OLEDs lag inorganic LEDs in brightness mainly because
comparatively little charge can be conducted through the resistive
transport layers (HTL or ETL). This well known effect is referred to as
Space Charge Limited Current. Simply put, due to the low mobility of

1 carriers in organic materials, a traffic jam develops which restricts the
flux of electrons and holes reaching the emission layer. Better emitter
materials cannot offer greatly improved brightness until high
conductance transport layers are also available.

5 3. Reliability: Organic LEDs degrade in air and during operation. Several
problems are known to contribute.

A) Efficient low field electron injection requires low work function
cathode metals like Mg, Ca, Li etc. which are all highly reactive in
10 oxygen and water. Ambient gases and impurities coming out of the
organic materials degrade the contacts.

B) Conventional AgMg and ITO contacts still have a significant
barrier to carrier injection in preferred ETL and HTL materials,
respectively. Therefore, a high electric field is needed to produce
15 significant injection current. Stress from the high field and ohmic
heating at the resistive electrode/organic interface contribute to device
degradation.

C) The high resistance of carrier transport layers heats the device
under operation.

20 D) Thermal stability of most OLED materials is poor making them
sensitive to heating. Upon heating, many amorphous organic materials
crystallize into grains. The crystallites have less volume and pack less
uniformly than the amorphous solid. The resulting gaps and odd
shapes of the crystallites make conduction from one crystallite to the
25 next difficult, increasing resistance and heating in a positive feedback
loop, while opening further channels for gaseous contaminants to
penetrate, or for neighboring materials to diffuse. The relationship
between crystallization in organic materials and the mobility is well
understood from the photoconductor literature in for example:
30 Borsenberger and Weiss, "Organic photoreceptors for imaging
systems", Marcel Dekker Inc., New York, 1993.

1 4. Poor chemical stability: Organic materials commonly used in OLEDs
are vulnerable to degradation caused by reaction with and diffusion of
contact electrode materials and the ambient atmosphere.

5 OLEDs are mainly limited by their contacts and transport layers, and
feedback from the transport layer heating. It is thus highly desirable to
replace the low work function metal based cathodes with a stable, possibly
transparent cathode characterized by barrierless charge injection into
10 OLEDs. It is also highly desirable to replace ITO anodes with a stable,
non-diffusive, and possibly transparent anode characterized by barrierless
charge injection into OLEDs.

However, present day solutions inhibit performance and degrade device
reliability. The price of distancing the active layer from the metal contacts
15 for higher recombination efficiency are ohmic voltage drops across the
HTL/ETL, leading to heating and power consumption. Low work function
metals are unstable and unreliable. ITO introduces impurities and has a
barrier to hole injection.

20 As can be seen from the above examples and the description of the state of
the art the contact materials need to be improved to realize OLEDs and
displays based thereon with superior characteristics. Little progress has
been recorded in the search for improved electrode materials, because
researchers have only searched within the known paradigm of what defines
25 a good electrode material: a material having a favorable work function.

The work function of a material is defined as the separation in energy
between the Fermi energy and the vacuum reference energy. In metals, one
can inject electrons from just below the Fermi energy, or holes from just
30 above the Fermi energy. There is no possibility of using other bands due to
the density of electrons. Although ITO is theoretically a wide bandgap
semiconductor, it corresponds to the classical metal-based model, as we
discuss below.

1 ITO is a wide bandgap semiconductor which has been successfully used to
inject holes into OLEDs. ITO is a highly degenerate n-type material
characterized by electron concentrations on the order of 10^{21}cm^{-3} . The ITO
conduction band is positioned at approximately the correct energy for
5 injecting holes into an organic HOMO, i.e. ITO has a large work function.
Because of the large electron concentration, the ITO Fermi energy, which
defines the work function for a given ITO sample, lies several 100 meV
above the conduction band. Above the Fermi level are empty states which
act as holes, and it is these holes, not ones in the VB, which are injected
10 into the organic material. Therefore, ITO electrodes inject via the exact
mechanism that a Au electrode does, from just above the Fermi energy, and
ITO does not fall under the inventive approach described below.

It is an object of the present invention to provide new and improved organic
15 EL devices, arrays and displays based thereon.

It is a further object of the present invention to provide new and improved
organic EL devices, arrays and displays based thereon with improved
efficiency, lower operating voltage, and increased stability and reliability.
20

It is a further object to provide a method for making the present new and
improved organic EL devices, arrays and displays.

25

30

SUMMARY OF THE INVENTION

The above objects have been accomplished by providing an OLED wherein at least one of the contact electrodes, either the cathode or anode, comprises a non-degenerate wide bandgap semiconductor (n-d WBS), i.e., a semiconductor having a bandgap greater than 2.5 eV. If the anode comprises a n-d WBS, this n-d WBS is to be chosen such that holes are injected from the valence band of the anode into the HOMO of the adjacent organic material. A n-d WBS cathode has to be chosen such that electrons are injected from the conduction band of the n-d WBS into the LUMO of the adjacent organic material.

The inventive approach depends on the fact that any semiconductor whose bandgap is comparable or greater than the bandgap of typical OLED materials, i.e. > 2.5 eV, will 'a priori' have its conduction and/or valence band positioned at a favorable energy level with respect to the organic HOMO or LUMO, respectively, such that injection of one or both carrier types can occur at low voltage across little or no energy barrier. The inventive approach also benefits from the many improved properties of semiconductors, especially non-degenerate wide bandgap semiconductors, for OLED electrodes, including good conductivity, transparency in the visible spectrum, chemical inertness, hardness, and ability to be deposited in the amorphous or polycrystalline state at extremely low temperatures on glass, organic thin films, or other amorphous or crystalline substrates. Plastic may also serve as substrate.

In one embodiment of the present invention, a single or multi-layer OLED structure having a n-d WBS cathode directly in contact with the corresponding organic layers, and a conventional opposite contact electrode is envisioned.

In another embodiment of the present invention, a single or multi-layer OLED structure having a n-d WBS anode directly in contact with the

1 corresponding organic layer, and a conventional opposite contact electrode is envisioned.

In another embodiment of the present invention, a single or multi-layer
5 OLED structure having both a n-d WBS anode and a n-d WBS cathode directly in contact with the corresponding organic layer is envisioned.

In another embodiment of the present invention, an OLED structure having a
n-d WBS electrode whose performance is improved by introducing a second
10 and/or third semiconductor is envisioned. The second semiconductor is in direct contact with the corresponding organic layer, and is characterized by an improved matching of the injecting band to the corresponding organic layer molecular orbital. The second semiconductor might be an alloy of the
n-d WBS, or it might be a wholly different semiconductor. The third
15 semiconductor is farthest from the organic layers, and is characterized by the ability to form an improved ohmic contact to a highly conducting lateral transport layer. The third semiconductor might also be an alloy of the n-d WBS, or it may be a wholly different semiconductor.

20 In yet another embodiment of the present invention, an OLED in which a n-d WBS injecting layer is in direct contact to the nearest organic layer, but has a thin embedded metal interlayer very near to the n-d WBS/organic interface. The metal can be selected for its work function, properties as a
diffusion barrier between the organic materials and the n-d WBS, or
25 transparency, and serves the purpose of further improving the stability or electron injection of the n-d WBS/organic interface. The n-d WBS on the opposite side of the thin embedded metal layer can be the same n-d WBS, or a different n-d WBS.

30 In yet another embodiment of the present invention, an OLED in which a n-d WBS electrode is separated from the nearest organic layer by a thin metal interlayer is envisioned. The metal can be selected for its transparency, work function, or properties as a barrier between the organic materials and

1 n-d WBS, and serves the purpose of further improving the stability or
electron injection of the n-d WBS/organic Interface.

The introduction of a n-d WBS based-electrode leads to the following
5 advantages:

1. Low voltage carrier injection is realized through the highly favorable
alignment of the n-d WBS energies with respect to preferred OLED
materials.
10
2. n-d WBS's are highly transparent to visible light.
3. n-d WBS's are chemically inert and thermally stable and therefore have
no undesirable solid state interactions with the organic layers with
15 which it is in contact or close proximity.
4. n-d WBS's are an outstanding encapsulant and mechanical protectant
material for OLEDs, due to their nearly amorphous state and low
impurity diffusion rates.
20
5. n-d WBS's can be deposited at conditions required for OLED formation
(e.g. low temperature, amorphous substrates, minimum damage to the
growth surface) in a conductive state.
- 25 6. n-d WBS's quench optical recombination in nearby organic layers less
strongly than metals enabling reduced transport layer thicknesses.

DESCRIPTION OF THE DRAWINGS

The invention is described in detail below with reference to the following schematic drawings (it is to be noted that the drawings are not drawn to scale):

FIG. 1A shows a known OLED having an emission layer and two electrodes.

FIG. 1B shows another known OLED having an emission layer and two metal electrodes, with work functions chosen such that the energy barrier for carrier injection is reduced.

FIG. 2A shows another known OLED having an emission layer and two metal electrodes, the work function of the anode being chosen such that the energy barrier for hole injection is low, whereas the work function of the cathode poorly matches the emission layer yielding little electron injection and little radiative recombination in said emission layer.

FIG. 2B shows another known OLED having an emission layer with low electron mobility compared to hole mobility such that the recombination occurs close to the cathode where it is quenched.

FIG. 3 shows another known OLED having an electron transport layer and hole transport layer.

FIG. 4 shows the three possible types of band lineups between the conduction bands (CB) and valence bands (VB) of a n-d WBS and the lowest unoccupied molecular orbital (LUMO) and highest occupied molecular orbital (HOMO) of an organic material which is in contact with the n-d WBS. (A) CB is above

1 the LUMO, VB is above the HOMO: This interface can inject
electrons into the organic. (B) n-d WBS has a bandgap slightly
smaller than the organic. CB is below the LUMO, VB is slightly
above the HOMO: This interface can efficiently inject holes into
5 the organic over the small barrier. (C) CB is above the LUMO,
VB is below the HOMO: The ideal case; injection of either
polarity, dependent on the bias direction, can occur at low
voltage.

10 **FIG. 5** shows a minority carrier organic contact electrode scheme
relying on alloying for band matching.

FIG. 6 shows a majority carrier organic contact electrode scheme
relying on alloying for band matching to the organic and an
15 ohmic contact to the lateral transport layer material.

FIG. 7 shows the band structure measured by ultraviolet
photoemission spectroscopy for a GaN/Alq3 heterojunction.
Experimental error is included in the Alq3 bands as drawn. The
20 data show that GaN/Alq3 corresponds to the bipolar injection
case of Figure 4 (C). Experiments have confirmed that both
GaN anodes and cathodes inject charge at low voltage.

FIG. 8 shows the I-V and EL-V characteristics for a GaN-based
25 cathode-up OLED structure fabricated in our laboratory. The
excellent diode characteristics and the 4.8 V onset of EL are
proof of the outstanding qualities of GaN cathodes, even when
deposited on top of organic materials.

30 **FIG. 9** shows a cross-section of the first embodiment of the present
invention.

1 **FIG. 10** shows a cross-section of the second embodiment of the present invention.

5 **FIG. 11** shows a cross-section of the third embodiment of the present invention.

FIG. 12 shows a cross-section of the fourth embodiment of the present invention.

10 **FIG. 13** shows a cross-section of the fifth embodiment of the present invention.

FIG. 14 shows a cross-section of a display or array, according to the present invention.

15 **FIG. 15** shows a cross-section of a display or array, according to the present invention.

20 **FIG. 16** shows a cross-section of a display or array, according to the present invention.

FIG. 17 shows a cross-section of a display or array, according to the present invention.

25

30

1

GENERAL DESCRIPTION

The basis of the present invention is the realization that a n-d WBS has either its conduction band (CB) or valence band (VB) or both positioned at a favorable energy level to inject charge into common OLED materials. In order to evaluate n-d WBS's as electrode materials, an ideal OLED electrode must first be defined.

10

An ideal contact electrode material should be characterized by:

1. High transparency in the visible spectrum and low quenching of nearby radiative recombination to permit flexibility in the direction of light extraction and the design thickness of organic layers.
- 15 2. One or more favorable energy band levels for low voltage injection of charge into preferred OLED materials.
3. Sufficient electrical conductivity such that total vertical device series resistance is unaffected by the electrode. The electrode material need not be extremely conductive since additional highly conductive layers can be added to enhance the lateral conductivity.
- 20 4. Depositability onto organic layers or amorphous, crystalline or polycrystalline substrates at low temperatures with no damage to the underlying material.
- 25 5. Chemical inertness
6. Low diffusivity of impurities
- 30 7. Mechanical hardness and thermal stability

1 Item 1 is satisfied because n-d WBS's are by definition transparent to most
or all of visible light. This is because few electronic states exist within the
forbidden gap of 2.5 eV or more, meaning that negligible absorption occurs
for photons having energies below the semiconductor bandgap.

5 Item 2 is satisfied because the bandgap of a n-d WBS is comparable or
larger than that of common OLED materials. This means that either the CB,
VB, or in some cases both bands (see Figure 4 (C)), are situated at
favorable energy levels with respect to a LUMO or HOMO of a particular
10 OLED material. In short, if a n-d WBS, does not efficiently inject holes into
an OLED material, it must inject electrons efficiently, or vice versa.
Furthermore, due to the tendency of electron transporting organic materials
to have LUMOs lower in energy than hole transporting materials, and hole
transporting materials to have HOMOs higher in energy than electron
15 transporting organic materials, nature cooperates to make n-d WBS good
injectors of both polarities for preferred OLED device embodiments. Some
typical n-d WBS band alignments with respect to organic molecular orbital
energies are illustrated in Figures 4 (A) - (C) with the point of illustrating
that in all cases, at least one n-d WBS band is positioned for charge
20 injection across a small or non-existent energy barrier into its molecular
orbital counterpart in the organic material.

Item 3 is satisfied because semiconductors can be doped, or conduct as a
result of native defects or intrinsic carriers, and have much higher mobilities
25 than common OLED materials. Even most intrinsic n-d WBS's are more
conductive than common OLED materials, and will not be the limiting
resistive voltage drop in the vertical device structure.

Item 4 is satisfied because most known n-d WBS's are also semiconducting
30 in their amorphous or polycrystalline states, obtained when deposited at low
temperature. Common semiconductor growth techniques are capable of
depositing material at temperatures low enough to be compatible with
common OLED substrates, and even below the glass transition temperatures

1 of common OLED materials. Techniques which are compatible with OLED
technology are chemical vapor deposition, plasma enhanced chemical vapor
deposition, laser ablation, evaporation, molecular beam deposition (MBD),
and plasma enhanced MBD.

5 Items 5-7 are also satisfied for n-d WBS's, which generally have relatively
ionic or strong covalent bonds. Such bonds are much stronger than those of
organic materials which are weakly bound by intermolecular van der Waals
bonding.

10 To summarize the state of the art in contrast to the inventive approach,
highly conducting materials, be they metals or degenerate semiconductors
such as ITO, inject their carriers from their Fermi energy level. They are
effectively one band systems, and are limited by their work functions. It is
15 notable that ITO's VB is extremely favorably positioned to act as a hole
injector, being some 3-4 eV below most organic HOMO's in energy. This is
due to the fact that ITO is indeed a wide bandgap semiconductor, and as we
argue therefore has at least one band capable of low voltage injection.
However, the ITO VB is useless for hole injection because of the degenerate
20 n-type nature of ITO, which dictates that no free holes exist in the VB, and
that holes injected in the ITO VB have a negligible mean free path before
recombining with the plethora of electrons present. Again, this is precisely
the physics of metals, which also have many bands, but only one band in
which conduction can occur.

25 In contrast, the inventive approach is based on the fact that in a 'n-d WBS',
either the VB is favorably positioned for hole injection, or the CB is
favorably positioned for electron injection, or both. By 'n-d WBS', we mean
a WBS whose carrier concentration is moderate enough such that it behaves
30 like a semiconductor, as opposed to a metal, in the sense that it has a
moderate enough carrier concentration to enable either band to be used for
injection into the organic. In the minority carrier transport case (i.e. holes
through an n-type semiconductor or electrons through a p-type

1 semiconductor), the semiconductor must be largely depleted of majority
carriers to support minority carrier transport over a useful and practical
distance without recombination. A practical upper free carrier concentration
limit is roughly 10^{20}cm^{-3} , which corresponds to a depletion width of 1 - 3 nm
5 (depending on the semiconductor dielectric constant). If the carrier
concentration is so large that no more than 1 - 3 nm of material can be
depleted for the purposes of minority carrier transport, then the material
does not meet the criteria to be an 'a priori' good electrode material of at
least one polarity, since the minority carrier polarity can never be injected
10 by a film of useful and practical thickness. Such a highly doped
semiconductor may still be a good majority carrier electrode if its majority
carrier band is positioned favorably in energy compared to common organic
organic molecular orbitals, but this case falls under the old paradigm, i.e. a
degenerate semiconductor is only capable of injecting charge from its Fermi
15 level, and does not fall under the present invention. Further details on
semiconductors can be taken from "Physics of Semiconductor Devices," S.
Sze, Pub: John Wiley and Sons, New York, 1981.

Many WBS are similar to ITO in so far as it is difficult or impossible to
20 control their carrier concentrations. However, so long as the carrier
concentrations involved are moderate, $< 10^{20}\text{cm}^{-3}$, then the concept
presented above is valid. The reason is that a useful and practical thickness
of the respective semiconductor can be depleted by an additional metal or
semiconductor on the opposite side of the organic layer stack. This
25 depletion permits erstwhile minority carriers to be transported through the
non-majority carrier band, e.g. valence band in an equilibrium n-type
semiconductor, to capitalize on a favorable energy level for injection in that
band. Without the depletion, minority carriers would recombine with
majority carriers before they could be injected into the organic. Such
30 recombination events directly degrade overall device operating efficiency.
Simply put, a n-d WBS is one in which a useful thickness can be depleted by
an adjacent metal to permit both semiconductor bands to be utilized, in

- 1 principle, for carrier injection into their organic molecular orbital counterparts.

Another advantage of semiconductors is that their bandgaps and band
5 energies normally vary continuously when alloyed with an isoelectronic element or another semiconductor, in which a single component is replaced by an isoelectronic element. For example, the bandgap of Si can be continuously varied by the addition of Ge, or GaAs can be varied by the addition of either InAs or AlAs. Similarly, the bandgaps and band energies
10 can also be varied by alloying with a different semiconductor, e.g. AlN and SiC. The ability to grade an alloy concentration across a semiconducting electrode has several useful properties, including the ability to tune the band energies by varying the alloy concentration, the ability to eliminate barriers to carrier transport, and the ability to use a smaller bandgap
15 material as an ohmic contact to the electrode.

In general, two types of contacts to organic material can be formed by a non-degenerate semiconductor electrode. This is in contrast to the case of degenerate semiconductors and metals in which injection of electrons or
20 holes is only possible from the Fermi energy level. These two contact schemes are referred to by us as minority and majority carrier contacts, respectively. The formation of a minority carrier contact, incorporating graded alloys to improve ohmic contacts and injection, is illustrated in Figure 5 for a non-degenerate wide bandgap semiconductor which has a
25 n-type conductivity, but is used as an anode electrode for hole injection, i.e. for minority carrier injection. What is discussed below also applies to the case of a p-type semiconductor which is used to inject electrons. Near the organic film, the semiconductor is alloyed (by introduction of AlN to GaN, for example) to increase the bandgap and lower the VB energy so that there
30 is no barrier to injection into the organic material HOMO. On the other side, the semiconductor is alloyed (e.g. by adding InN to GaN) to decrease the bandgap so that the VB energy is raised to match that of a hole injecting metal or ITO. On both sides, the alloy content is graded so that the shift in

- 1 the VB (or CB in the electron injection case) is smooth. Overall, the holes
see no abrupt barriers, although voltage is necessary to drive them into the
organic. Because holes are a minority carrier in this system, the entire
semiconducting region must be thin enough that it is largely depleted of
5 electrons by the metal or ITO hole injecting layer. This can be accomplished
in a semiconducting film of practical and useful thickness (> 1 nm) only in a
non-degenerate semiconductor with $< 10^{20} \text{cm}^{-3}$ carrier concentration, as
discussed above.
- 10 The formation of a majority carrier contact, incorporating graded alloys to
improve ohmic contacts and injection, is illustrated in Figure 6 for a n-d
WBS, also n-type for the purpose of this example, which is used to inject
electrons into the organic LUMO. As in Figure 5, the polarity could be
changed to p-type, and the arguments would be the same. The wider
15 bandgap alloy and grading retain their functions of matching the electrode
to the LUMO and avoiding barriers in the alloy transition regions. The
smaller bandgap alloy can, as in the case of Figure 5 allow the material to
better match the work function of an electron injecting metal, e.g. Al. Or, as
shown in Figure 6, the small bandgap alloy, if it has a high carrier density,
20 can be used to form an ohmic contact to a material not matched in energy
to its CB, but is otherwise desirable, such as ITO (useful for its combination
of transparency and conductivity). The carrier concentration of
semiconductors at the temperatures of interest to the present invention
generally increases as the bandgap decreases for several reasons,
25 including an increase of intrinsic carriers, and shallower dopant and defect
levels. Therefore, it is advantageous to alloy down to a smaller bandgap to
exploit ohmic tunneling contacts. For example, we have successfully
injected electrons from ITO into an OLED through a GaN cathode graded
down to an InN ohmic contact layer. This was despite the large differences
30 in the InN and ITO work functions, and was successful because the
depletion widths of each heavily doped material were thin enough to be
tunneled through, consistent with well known principles of semiconductor
physics for the formation of ohmic contacts. We further note for clarity that

1 InN in the above example is not a n-d WBS. In general, semiconductors
having bandgaps less than 2.5 eV are often useful as ohmic contact layers in
the inventive n-d WBS based contact scheme. This is because a thin contact
layer suffices for the purpose of ohmic contact formation, which given the
5 low absorption coefficient of even smaller bandgap semiconductors in
comparison to metals, means that the addition of a thin and useful ohmic
contact layer does not markedly increase absorption losses in the device.
Therefore, n-d WBS based contacts incorporating smaller bandgap
semiconductor ohmic contact layers can still yield a highly transparent
10 overall contact electrode.

GaN illustrates the above arguments and the present invention nicely, but
they apply equally well to non-degenerate wide bandgap semiconductors in
general, provided they meet the criteria detailed above. Examples of other
15 non-degenerate wide bandgap semiconductors which could be useful
electrode materials are non-degenerate wide bandgap III-N compounds
such as GaN, AlN, BN, AlGa_N, InGa_N, InAlGa_N, or II-VI compounds such as
ZnS, MgS, ZnSe, MgSe, ZnMgSSe, CdS, ZnO, BeO, or more exotically
non-degenerate wide bandgap semiconductors such as diamond, SiC or
20 ZnGaSSe, CaF₂, AlP, just to mention some. It also applies to
non-degenerate wide bandgap compounds which are doped to modify their
electrical conductivity.

Figure 7 shows results of an ultraviolet photoemission spectroscopic (UPS)
25 investigation of a GaN/organic (Alq₃) heterojunction. With UPS, one
observes the position of the GaN valence band with respect to the Alq₃
HOMO. Taking into account the known energy separation between the GaN
VB and CB (i.e. the GaN bandgap energy of 3.39 eV) and the Alq₃ HOMO
and LUMO, the full band structure, as displayed in Figure 7, is elucidated.
30 The data show that both the CB and the VB of GaN are favorably positioned
for charge injection into the Alq₃. This also indicates that the GaN VB is
positioned favorably in energy to barrierless hole injection into preferred
OLED HTL materials, which as we discussed above, tend to have their

- 1 HOMO energies higher than that of the electron transporting Alq3 HOMO level.

Further confirmation of the favorable positioning of the GaN bands comes
5 directly from OLED devices fabricated in our laboratory. Figure 8 are the
(left axis, linear scale) current-voltage and (right axis, log scale)
electroluminescence-voltage characteristics for an OLED having the
following structure: Glass/ITO/CuPc/NPB/Alq3/GaN-based cathode. The
device shows excellent diode characteristics with low reverse bias current
10 levels, and an onset of efficient electroluminescence at only 4.8 V indicating
that the GaN cathode can inject electrons into Alq3 at low voltage, i.e. there
is little or no barrier to electron injection. It is also notable that in the device
of Figure 8, the GaN was deposited directly onto the OLED stack by plasma
enhanced molecular beam deposition, thereby directly demonstrating that a
15 n-d WBS can successfully be deposited onto OLED materials, thereby
satisfying item 4 on the above list of properties of an ideal electrode.

Numerous GaN cathode and anode devices fabricated in our laboratory with
the n-d WBS deposited on the top of or below the organic layers confirm the
20 data of Figure 8 that GaN, because it is a n-d WBS with both favorable CB
and VB energy levels for carrier injection into OLEDs, is both an excellent
anode and cathode for common OLED device structures, consistent with the
inventive approach outlined above.

25 The simplest embodiment of the present invention, already improved with
respect to the state of the art is depicted in Figure 9. from the substrate up,
listed in the order of deposition, is a glass/n-d WBS/ETL/HTL/Metal OLED
structure. In addition to the eliminated or reduced barrier afforded by the
cathode 61 comprising a n-d WBS formed on the glass substrate 60, the ETL
30 62 thickness may be reduced as a result of reduced optical quenching and
the conventional ITO anode can be replaced by a higher work function, less
diffusive metal since the anode 64 is no longer the transparent contact. We
note here that the structure depicted in Figure 9 might also benefit from an

1 additional layer or layers (e.g. InGaN or ITO/InGaN) between the GaN
cathode and glass 60 to lower the lateral sheet resistance of the cathode 61,
provided that the additional layer, serving as lateral transport layer, also
forms a good ohmic contact to the n-d WBS cathode. This additional layer is
5 deemed to form part of the cathode. Finally, any substrate, even an opaque
one, can replace the glass substrate 60 depicted. In this case, the preferred
embodiment would have a transparent top contact 64, e.g. ITO in the case of
a cathode 61 comprising a n-d WBS. The organic region 65 of the first
embodiment comprises an ETL 62 and HTL 63. It is to be noted that the
10 present Figure and all other Figures are not drawn to scale.

Table 1: Exemplary details of the first embodiment

Layer	No.	Material	Thickness	present example
substrate	60	glass	0.1mm-5mm	1mm
cathode	61	GaN	10-1000nm	50nm
ETL and EL	62	Alq3	20-1000nm	80nm
HTL	63	TAD	5-500nm	50nm
anode	64	Au	10-2000nm	50nm

25 A second embodiment, a n-d WBS anode device, is depicted in Figure 10.
From the substrate 70 up, listed in the order of deposition, is a
glass/metal/ETL/EL/HTL/n-d WBS anode OLED structure. The major
difference between Figure 9 and Figure 10 is that the anode 75 comprising
a n-d WBS is deposited last on top of the organic layer stack 76, which in
30 this case includes a separate emission layer 73 (EL), as is sometimes
practiced in the art. Also, the anode 75 might comprise an additional layer
or layers, such as an ohmic contact contact or lateral transport layer 75.2,
for example, as illustrated in Figure 10. In the case of an ohmic contact

layer 75.2, an additional metal or ITO top layer (not shown) would be advantageous for lateral conduction. Any substrate other than glass can be chosen, even an opaque one. In the latter case, the anode 75 is preferably designed to be fully transparent for ease of light extraction. The organic region 76 of the second embodiment comprises an ETL 74, a layer 73 suited for electroluminescence (EL) and HTL 72.

Table 2: Exemplary details of the second embodiment

Layer	No.	Material	Thickness	present example
substrate	70	glass	0.1mm-5mm	1mm
cathode	71	MgAg	10-300nm	50nm
ETL	72	Alq3	5-500nm	20nm
EL	73	coumarine-doped Alq3	20-1000nm	70nm
HTL	74	TAD	5-500nm	50nm
anode contact	75.1	GaN	10-2000nm	50nm
ohmic contact layer	75.2	InGaN	10-2000nm	50nm
outer anode (not shown)	75.3	ITO	10-2000nm	50nm

We would like to note that the devices depicted in Figures 9 and 10 would function equally well in n-d WBS anode down or n-d WBS cathode up architectures, respectively, provided that the polarity of the organic layers and the choice of opposite electrode materials are suitably altered. E.g., the device depicted in Figure 9 could be modified to have a Glass/n-d

- 1 WBS/HTL/ETL/MgAg structure, and the device depicted in Figure 10 could be modified to have a Glass/ITO/HTL/EL/ETL/n-d WBS structure.

5 A third embodiment of the present invention is depicted in Figure 11. From the substrate 80 up, listed in the order of deposition, this embodiment comprises glass/n-d WBS anode/HTL/(ETL, EL)/OIL/n-d WBS cathode. This structure functions much like the devices of Figures 9 and 10, except the device is further improved by having both contacts comprising n-d WBS's. The organic region 85 of the third embodiment comprises a combined
10 ETL/EL layer 83 and a HTL 82, as is often practiced in the art. We have also added an organic injection layer (OIL) 83.2. The OIL might have the properties that it is less sensitive to damage caused by the deposition of the n-d WBS cathode, or that it has a LUMO energy intermediate between that of the n-d WBS 84.1 CB and the ETL 83.1 LUMO, further reducing the
15 magnitude of any barrier which might be present to electron injection.

20

25

30

Table 3: Exemplary details of the third embodiment

Layer	No.	Material	Thickness	present example
substrate	80	silicon	0.1mm-5mm	2mm
sub-anode	81.1	ITO	10-300nm	50nm
ohmic contact	81.2	MgCdSTe	10-300nm	50nm
anode	81.3	MgS	10-300nm	50nm
HTL	82	TAD	5-500nm	50nm
ETL and EL	83.1	Oxadiazole	50-1000nm	70nm
OIL	83.2	organic	2nm-200nm	15nm
cathode	84.1	AlGaIn	10-2000nm	50nm
ohmic contact layer	84.2	InGaIn	10-2000nm	50nm
outer cathode	84.3	ITO	10-2000nm	50nm

A fourth embodiment of the present invention is depicted in Figure 12. From the substrate 90 up, listed in the order of deposition, is a glass/metal/HTL/(ETL, EL)/metal/n-d WBS OLED structure. This structure capitalizes on a more conductive alloy 94.3 of the primary n-d WBS 94.2 on the outer cathode side to facilitate an ohmic contact to the outer cathode as discussed in relation to Figure 6. In addition, the thin metal 94.1 interlayer has the additional advantages of improving injection via a low metal 94.1 work function, or improving reliability and stability by protecting the organic layer stack 85 from the n-d WBS cathode 94 deposition and/or cross diffusion and/or chemical reactions. The concept of advantageously alloying

the n-d WBS electrode illustrated in Figure 12 is equally valid for related embodiments incorporating e.g. a n-d WBS based anode, or a minority carrier n-d WBS contact of either polarity as discussed in relation to Figure 5. The concept of the thin metal 94.1 interlayer is equally valid for anode formation, provided the metal be chosen for its high work function if its chief role is to enhance hole injection. If the role of the thin metal 94.1 interlayer in the anode is primarily to form a barrier, then a low work function metal could also be used for anode formation, provided that the metal is thin, or largely consumed by chemical reactions with the adjacent organic layer or the n-d WBS based contact.

Table 4: Exemplary details of the fourth embodiment

Layer	No.	Material	Thickness	present example
substrate	90	silicon	0.1mm-5mm	5mm
anode	91	Au	10-300nm	50nm
HTL	92	TAD	5-500nm	50nm
ETL and EL	93	Alq3	20-1000nm	70nm
thin metal	94.1	Ca	0.01-10nm	1nm
cathode	94.2	GaN	10-2000nm	50nm
ohmic contact layer	94.3	InGaN	10-2000nm	50nm
outer cathode	94.4	ITO	10-2000nm	50nm

Figure 13 depicts an OLED structure in which a n-d WBS cathode 104 comprises and encapsulates an embedded thin low work function metal 104.2 (TM) interlayer near the cathode/organic interface. The TM can

1 function as a chemical, mechanical, protective or diffusion barrier, or
 improve electron injection by creating a dipole or providing electrons to the
 CB of the n-d WBS 104.1 adjacent to the ETL 103. It can also be highly
 transparent since only small quantities are necessary. The organic region
 5 105 of the fourth embodiment comprises a combined ETL/EL layer 103 and a
 HTL 102.

Table 5: Exemplary details of the fifth embodiment

10	Layer	No.	Material	Thickness	present example
	substrate	100	glass	0.1mm-5mm	1mm
	anode	101	ITO	10-300nm	50nm
15	HTL	102	TAD	5-500nm	50nm
	ETL and EL	103	Alq3	20-1000nm	70nm
	cathode interlayer	104.1	ZnS	1-20nm	5nm
20	TM	104.2	Li	1-20nm	2nm
	cathode	104.3	GaN	10-200nm	50nm
	ohmic contact	104.4	InGaN	10-200nm	20nm
25	outer cathode	104.5	ITO	10-2000nm	20nm

We note that the thin encapsulated metal concept is equally valid for
 30 anodes, provided that the metal is a high work function metal if its primary
 role is to enhance hole injection. This concept is also equally valid for n-d
 WBS based contacts grown either before or after the deposition of the
 organic stack. Finally, there is no reason that the n-d WBS on either side of
 the TM must be the same material. In fact, certain advantages are obtained

1 if they are different materials. For example, it may be desirable to have a
n-d WBS interlayer 104.1 which can be gently evaporated onto the organic
surface, or is otherwise harmless to the organic, in direct contact to the
organic, even if the n-d WBS interlayer 104.1 does not have otherwise
5 favorable properties, for example a barrier to injection or poor conduction.
These two problems can be solved because electrons from the adjacent TM,
provided the outer n-d WBS 104.3 has a higher CB energy, will be
transferred to the n-d WBS 104.1 in direct contact to the organic which will
raise its Fermi level above the CB and lower the barrier to electron injection
10 and also provide conduction electrons. Another example is if the n-d WBS
interlayer 104.1 in direct contact with the organic which has a higher CB
energy than the TM Fermi level. In this case, if the n-d WBS 104.1 is made
thin enough, electrons from the TM can tunnel through the intervening n-d
WBS 104.1 and still achieve low voltage injection. This approach might
15 permit the use of a highly insulating n-d WBS, without regard for the
difficulties of injecting electrons into it or providing conduction electrons.

In the following, some display embodiments, based on and enabled by the
present invention, are disclosed.

20 It would be advantageous if one could integrate OLEDs onto Si substrates
because prior to OLED deposition, the substrate could be fabricated to
contain active Si devices, such as for example an active matrix, drivers,
memory and so forth. Such a structure can be a very inexpensive small
25 area organic display with high resolution and performance realized
primarily in the Si. An OLED, OLED arrays or an OLED display may either
be grown directly on such a Si substrate carrying Si devices, or it may be
fabricated separately and flipped onto the Si substrate later. A problem is
the Si metallization. Traditional OLED cathode metals are not stable in Si
30 processes or air. Another problem is that a transparent top contact is
needed because Si is not transparent. The present invention offers a
solution to these problems. The disclosed n-d WBS based electrodes permit
a stable, low voltage contact of either polarity to be formed on top of the

1 standard Si process metallizations, and are therefore compatible with OLED
technology. In addition, n-d WBS based electrodes might not require
patterning, which would save manufacturing by permitting the finished Si IC
substrate to be inserted directly into the OLED deposition process. The low
5 conductivity of n-d WBS's in comparison to conventional metal contact
materials means that if the n-d WBS based contact is deposited in blanket
fashion over the entire Si IC, conduction occur primarily in the vertical
direction in which the dimensions are small (on the order of 50 nm), while
negligible conduction in the lateral direction (on the order of 1 μm) would
10 occur. Controlling lateral current conduction is critical to avoid crosstalk
between pixels. Both n-d WBS based cathodes and anodes can be
deposited to form transparent top electrodes to allow light extraction above
the substrate plane. Finally, n-d WBS based anodes, in particular, deposited
before the deposition of the OLED device are also advantageous for
15 displays compared to the conventional ITO or Au metallization approach, for
reasons of stability and reliability, as well as lower voltage injection.

An organic array or display structure formed on a Si substrate is illustrated
in Figure 15 and described in the following. This display comprises a Si
20 substrate 120 which has integrated circuits comprising active and/or passive
devices such as memory cells, drivers, capacitors, transistors etc. (these
devices are not shown). On top of the Si integrated circuit, a stable OLED
anode (e.g. a n-d WBS based anode according to the present invention, or
otherwise a conventional ITO, Au, Ni, Pt or Cr anode) 121 is patterned to
25 connect the Si devices to the OLEDs 122. An OLED 122, in the cathode-up
geometry is deposited on the patterned anodes 121 and Si substrate 120.
Finally, a n-d WBS based cathode 123 is provided. It is to be noted that no
details of the OLED(s) are shown for sake of simplicity, but the OLED may be
any color, even white. In the case of white or blue OLED devices, full color
30 display function could be realized by patterning color filter and/or
conversion layers respectively, above the transparent cathode 123, or by
flipping a patterned array of color filters or converters onto the transparent
cathode 123. An advantage of n-d WBS based contacts is that the top

1 cathode 123 would make the organic device 122 resistant to the required
patterning steps because of its properties as an encapsulant. Finally, we
note that the use of a Si IC substrate enables the top cathode 123 to be
common to all devices, which avoids expensive and difficult patterning or
5 wiring of the individual pixel top electrodes.

For example, an Al-metallized Si chip 120 on which Au, ITO or InGaN/GaN
anodes 121 are patterned may serve as substrate for an OLED array or
display 122. One such OLED comprises (from the bottom to the top): a
10 stable anode layer, a HTL, an organic doped or undoped active region, an
ETL, and a cathode 123 which comprises GaN. This cathode 123 may for
example be composed of the following stack of 'layers':
MgSe/TM/GaN/InGaN/ITO.

15 Another array or display embodiment, where the OLEDs 132 have the anode
up, is illustrated in Figure 16. In this Figure, OLEDs 132 on top of a Si
substrate 130 are schematically shown. In this case, the Si substrate 130 is
partially covered by Al metal electrodes 131.1 which inject charge into the
n-d WBS cathodes 131. Other areas 130.1 do not conduct current. In
20 addition, the Si IC substrate 130 could be planarized during the back end of
the Si processing. This approach lowers processing cost because a blanket
n-d WBS based cathode 131 can be deposited immediately before OLED
deposition, and does not require additional patterning. As discussed above,
this is possible because the intended vertical current must traverse a
25 distance much smaller than the spacings between Al contact pads 131.1.
Simple geometry insures that little crosstalk will occur, even when the
anode 133 is common to all devices, as is shown in Figure 16. The top
anode 133 must be transparent since the Si substrate 130 is opaque to most
visible light. The top anode 133 could also be improved if a n-d WBS based
30 contact is used. The anode 133 could for example be composed of the
following stack of layers: AlGaIn/GaN/InGaIn/ITO. Color could also be
conveniently incorporated into the embodiment shown in Figure 16 by

- 1 means of color fillers and/or converters 134 which are deposited or patterned onto the transparent top contact.

5 The anode up embodiment on Si of Figure 16 may have advantages compared to the cathode up version of Figure 15 which arise from the generally higher hole mobilities in preferred HTL layers compared to electron mobilities in preferred ETL layers. If any damage to the upper organic layer occurs during electrode deposition, or contamination diffuses through the electrode and degrades the HTL, it could still have a higher mobility than the buried and ungraded ETL, and therefore not be the limiting factor in overall current conduction. Simply put, since the HTL initially outperforms the ETL in known OLED devices, the device is less sensitive to the initial stages of degradation of the HTL than the ETL.

- 15 Another possible display embodiment, illustrated in Figure 17, is described below. This display comprises a transparent substrate 140 on top of which amorphous-Si or poly-Si structures are formed using the same technology developed for active matrix liquid crystal displays. Usually the Si is structured to provide thin-film-transistors 141 (TFTs) and other devices, to produce an active matrix. Single crystal Si devices 141 thin enough to be highly transparent could also be transferred onto a glass substrate to perform largely the same function with improved performance compared to poly-silicon or amorphous Si circuits. These Si circuits 141 may then be covered or planarized by special layers 144. Color filters or color converters 142 can be provided, in addition, if the OLEDs 145 emit white or blue light, respectively. The Si devices 141 include structured n-d WBS based transparent cathodes or anodes 143, for example, onto which the OLEDs 145 can be deposited. The top electrode might also be a n-d WBS based contact, or a conventional contact. An advantage of this approach is that entrenched active matrix liquid crystal display (AMLCD) technology can be leveraged in combination with OLEDs to realize inexpensive, high performance AM displays over large areas. Furthermore, clever design permits light to be emitted through the glass substrate 140 so no

1 transparent top contact (anode 146) is needed. The anode 146 may be covered by a cap layer 147. The anode in this embodiment could also be n-d WBS based, and could even be made transparent if a surface emitting device were desirable.

5 The organic region of the present devices may - in addition to charge transport layers if needed at all - either comprise:

- a stack of more than one organic emission layers (EL), or
- 10 • an organic compound doped with one or more impurities, organic or inorganic, chosen to dominate and enhance the electroluminescence, or
- 15 • a stack of more than one organic emission layer, some of which may be doped to dominate or enhance the electroluminescence of that particular organic emission layers, or
- 20 • a stack of more than one organic layer, in which the role of one or more of said organic layers is to electrically confine one or more carrier types to improve the emission of an adjacent organic layer.

In the following some examples of the different organic materials which can be used are given.

25

Electron transport/Emitting materials:

Alq₃, Gaq₃, Inq₃, Scq₃, BAlq₃ (q means 8-hydroxyquinoline) and other 8-hydroxyquinoline metal complexes such as Znq₂, Beq₂, Mgq₂, ZnMq₂, BeMq₂, and AlPrq₃, for example. These materials can be used as ETL or
30 emission layer. Other classes of electron transporting materials are deficient nitrogen containing systems, for example oxadiazoles like PBD (any many derivatives), triazoles, for example TAZ (1,2,4-triazole). These functional groups can also be incorporated in polymers, starburst and spiro

1 compounds. Further classes are materials containing pyridine, pyrimidine,
 pyrazine and pyridazine functionalities. Finally, materials containing
 quinoline, quinoxaline, cinnoline, phthalazine and quinazoline functionalities
 are well known for their electron transport capabilities. Other materials are
 5 cyano-substituted polymers, didecyl sexithiophene (DPS6T),
 bis-triisopropylsilyl sexithiophene (2D6T). Azomethin-zinc complexes,
 pyrazine (e.g. BNVP), styrylanthracene derivatives (e.g. BSA-1, BSA-2),
 non-planar distyrylarylene derivatives, for example DPVBi (see C. Hosokawa
 and T. Kusumoto, International Symposium on Inorganic and Organic
 10 Electroluminescence 1994, Hamamatsu, 42), cyano PPV (PPV means
 poly(p-phenylenevinylene)) and cyano PPV derivatives.

The following materials are particularly well suited as

15 **Emission layers and Dopants:**
 Anthracene, pyridine derivatives (e.g. ATP), Azomethin-zinc complexes,
 pyrazine (e.g. BNVP), styrylanthracene derivatives (e.g. BSA-1, BSA-2),
 Coronene (also suited as dopant), Coumarin (also suited as dopant), DCM
 compounds (DCM1, DCM2; both also suited as dopants), distyryl arylene
 20 derivatives (DSA), alkyl-substituted distyrylbenzene derivatives (DSB),
 benzimidazole derivatives (e.g. NBI), naphthostyrylamine derivatives (e.g.
 NSD), oxadiazole derivatives (e.g. OXD, OXD-1, OXD-7),
 N,N,N',N'-tetrakis(m-methylphenyl)-1,3-diaminobenzene (PDA), Perylene and
 Perylene derivatives, phenyl-substituted cyclopentadiene derivatives,
 25 12-phthaloperinone derivatives (PP), squarillum dye (Sq),
 1,1,4,4-tetraphenyl-1,3-butadiene (TPBD), sexithiophene (6T),
 poly(2,4-bis(cholestanoxyl)-1,4-phenylene-vinylene (BCHA-PPV),
 Polythiophenes, quinacridones (QA) (see T. Wakimoto et al., International
 Symposium on Inorganic and Organic Electroluminescence, 1994,
 30 Hamamatsu, 77), and substituted quinacridones (MQA). Rubrene, DCJT (see
 for example: C. Tang, SID Conference San Diego; Proceedings, 1996, 181),
 conjugated and non-conjugated polymers, for example PPV and PPV
 derivatives (soluble precursor), MEH-PPV

- 1 (poly(2-methoxyl,5-(2'ethyl-hexoxy)-1,4-phenylene-vinylene), dialkoxy and
dialkyl PPV derivatives, segmented PPVs (see for example: E. Staring in
International Symposium on Inorganic and Organic Electroluminescence,
1994, Hamamatsu, 48, and T. Oshino et al. in Sumitomo Chemicals, 1995
5 monthly report).

Hole transport layers and Hole injection layers:

- The following materials are suited as hole injection layers and hole transport
layers. Materials containing aromatic amino groups, like TDP, NPB (see C.
10 Tang, SID Meeting San Diego, 1996, and C. Adachi et al. Applied Physics
Letters, Vol. 66, p. 2679, 1995), TPA, NIPC, TPM, DEH (for the abbreviations
see for example: P. Borsenberger and D.S. Weiss, Organic Photoreceptors
for Imaging Systems, Marcel Dekker, 1993). These aromatic groups can also
be incorporated polymers, starburst (for example: TCTA, m-MTDATA, see Y.
15 Kuwabara et al., Advanced Materials, 6, p. 677, 1994, Y. Shirota et al.,
Applied Physics Letters, Vol. 65, p. 807, 1994) and spiro compounds.
Further examples are: Cu(II) phthalocyanine (CuPc), NPB
(N,N'-diphenyl-N,N'-bis-(4-phenylphenyl)-1,1'-biphenyl-4,4'-diamine) distyryl
arylene derivatives (DSA), naphthalene, naphthostyrylamine derivatives (e.g.
20 NSD), Quinacridone (QA; also suited as dopant), poly(3-methylthiophene)
family (P3MT), Perylene and Perylene derivatives, polythiophene (PT),
3,4,9,10-perylenetetra-carboxylic dianhydride (PTCDA) (also suited as
isolator), tetra phenyldiaminodiphenyl (TPD-1, TPD-2, or TAD), PPV and
some PPV derivatives,
25 poly(2-methoxyl,5-(2'ethyl-hexoxy)-1,4-phenylene-vinylene (MEH-PPV),
poly(9-vinylcarbazole) (PVK), discotic liquid crystal materials (HPT).

- There are many other organic materials known as being good light emitters,
and many more will be discovered. These materials can be used as well for
30 making light emitting structures according to the present invention.
Examples of such materials are given in the publications cited in the
introductory portion of the present description. The contents of these
publications is herewith incorporated by means of reference.

1 Additionally, blend (i.e. guest host) systems containing active groups in a
polymeric binder are also possible. The concepts employed in the design of
organic materials for OLED applications are to a large extent derived from
the extensive existing experience in organic photoreceptors. A brief
5 overview of some organic materials used in the fabrication of organic
photoreceptors is found in the above mentioned publication of P.
Brosenberger and D.S. Weiss, and in Teltech, Technology Dossier Service,
Organic Electroluminescence (1995), as well as in the primary literatur.

10 OLEDs have been demonstrated using polymeric, oligomeric and small
organic molecules. The devices formed from each type of molecules are
similar in function, although the deposition of the layers varies widely. The
present invention is equally valid in all forms described above for polymeric
and oligomeric organic light emitting devices.

15 Small Molecule devices are routinely made by vacuum evaporation. This is
extremely compatible with PEMBD of GaN. Evaporation can be performed in
a Bell jar type chamber with independently controlled resistive and
electron-beam heating of sources. It can also be performed in a Molecular
20 Beam Deposition System incorporating multiple effusion cells and
electron-beam evaporators. In each case, GaN deposition can occur in the
same chamber, a vacuum connected chamber, or even a separate chamber
if some atmospheric contamination is tolerable.

25 Oligomeric and Polymeric organics can also be deposited by evaporation of
their monomeric components with later polymerization via heating or
plasma excitation at the substrate. It is therefore possible to alloy these by
co-evaporation also, and they are fully compatible with monomeric
compounds.

30 In general, polymer containing devices (single layer, multilayer, polymer
blend systems, etc.) are made by dissolving the polymer in a solvent and
spreading it over the substrate either by spin coating or the doctor blade

1 technique. After coating the substrate, the solvent is removed by heating or
otherwise. This method allows the fabrication of well defined multilayer
structures, provided that the respective solvents for each subsequent layer
do not dissolve previously deposited layers. Additionally, hybrid devices
5 containing both polymeric and evaporated small organic molecules are
possible. In this case, the polymer film is generally deposited first, since
evaporated small molecule layers cannot withstand much processing. More
interesting is the possibility of making a polymer/inorganic transport layer
on top of which monomeric layers are evaporated, possibly also
10 incorporating alloys. If the polymer is handled in an inert atmosphere prior
to introduction to vacuum, sufficient cleanliness for device fabrication is
maintained. In any case, the chemical inertness of GaN and other n-d WBS
makes it highly tolerant of polymer OLED processing.

15 To summarize, all inventions here are fully compatible to polymeric,
oligomeric, and small molecule OLED designs, or any hybrid design
thereof."

20

25

30

1 CLAIMS

1. Organic light emitting device having
 - a) a substrate,
 - 5 b) two contact electrodes, one thereof serving as anode and the other one serving as cathode, and
 - c) an organic region in which electroluminescence takes place if a voltage is applied between said two contact electrodes,said device being characterized in that at least one of said contact
10 electrodes comprises a non-degenerate wide bandgap semiconductor, such that, if said cathode comprises said non-degenerate wide bandgap semiconductor, electrons are injected from the conduction band (CB) of said non-degenerate wide bandgap semiconductor into the LUMO of
15 said organic region, or such that, if said anode comprises said non-degenerate wide bandgap semiconductor, holes are injected from the valence band (CB) of said non-degenerate wide bandgap semiconductor into the HOMO of said organic region.
2. The light emitting device of claim 1, wherein both contact electrodes
20 comprise a non-degenerate wide bandgap semiconductor.
3. The light emitting device of claim 1, wherein the sequence of layers is: substrate/cathode/organic region/anode.
- 25 4. The light emitting device of claim 3, wherein light generated by said electroluminescence is either emitted from said organic region through said anode, or from said organic region through said cathode and substrate.
- 30 5. The light emitting device of claim 1, wherein the sequence of layers is: substrate/anode/organic region/cathode.

- 1 6. The light emitting device of claim 5, wherein light generated by said
electroluminescence is either emitted from said organic region through
said cathode, or from said organic region through said anode and
substrate.
- 5 7. The light emitting device of claim 1, wherein said organic region
comprises a single organic layer or a stack of organic layers.
- 10 8. The light emitting device of claim 7, wherein said stack of organic layers
comprises an organic injection layer (83.2) introduced to mitigate
damage caused by the deposition of said non-degenerate wide bandgap
semiconductor contact onto said stack of organic layers.
- 15 9. The light emitting device of claim 1, wherein said non-degenerate wide
bandgap semiconductor is alloyed introducing a semiconductor,
preferably a semiconductor which differs by an isoelectronic element.
- 20 10. The light emitting device of claim 1, wherein said contact electrode
comprising a non-degenerate wide bandgap semiconductor comprises
an interlayer, preferably a metal interlayer.
- 25 11. The light emitting device of claim 10, wherein said interlayer is either in
direct contact with said organic region, or embedded within said
non-degenerate wide bandgap semiconductor.
- 30 12. The light emitting device of claim 1 or 2, wherein said organic region
comprises an electron transport layer being in direct contact with said
cathode and/or a hole transport layer being in direct contact with said
anode.
13. The light emitting device of claim 1, wherein said substrate is
transparent or semitransparent or opaque.

- 1 14. The light emitting device of claim 1, wherein said substrate consists of Silicon, glass or plastic.
15. The light emitting device of claim 1, wherein said substrate is flexible.
- 5 16. The light emitting device of claim 1, wherein said substrate is a Silicon substrate (140) comprising integrated circuits (141).
- 10 17. The light emitting device of claim 1, wherein said non-degenerate wide bandgap semiconductor is either
- a wide bandgap III-N compound such as GaN, AlN, BN, AlGa_N, InGa_N, InAlGa_N, or
 - a wide bandgap II-VI compound, such as ZnS, MgS, ZnSe, MgSe, ZnMgSSe, CdS, ZnO and BeO, or
 - 15 • diamond, SiC, ZnGaSSe, CaF₂, AlP.
18. The light emitting device of claim 1, wherein at least one of said contact electrodes comprises an Indium-Tin-Oxide (ITO) layer (75.3; 81.1, 84.3; 94.4; 101, 104.5).
- 20 19. The light emitting device of claim 1, wherein said organic region comprises either
- a stack of more than one organic emission layers (EL), or
 - an organic compound doped with one or more impurities, organic or inorganic, chosen to dominate and enhance the electroluminescence, or
 - 25 • a stack of more than one organic emission layer, some of which may be doped to dominate or enhance the electroluminescence of that particular organic emission layers, or
 - 30 • a stack of more than one organic layer, in which the role of one or more of said organic layers is to electrically confine one or more carrier types to improve the emission of an adjacent organic layer.

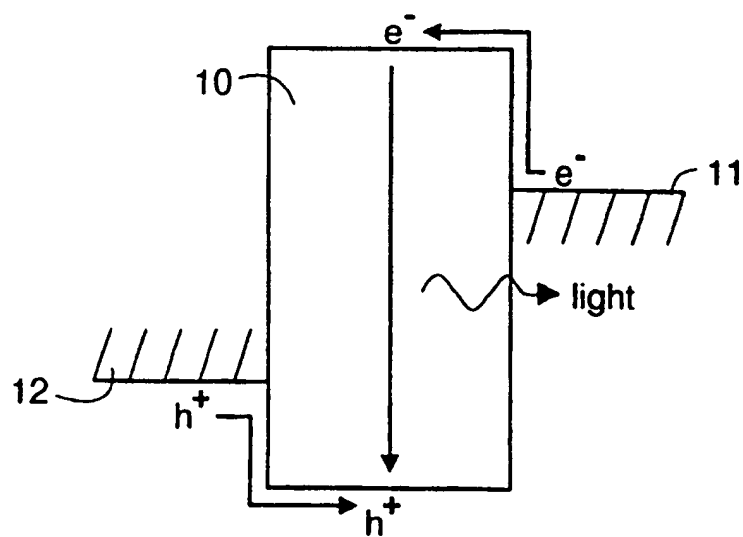
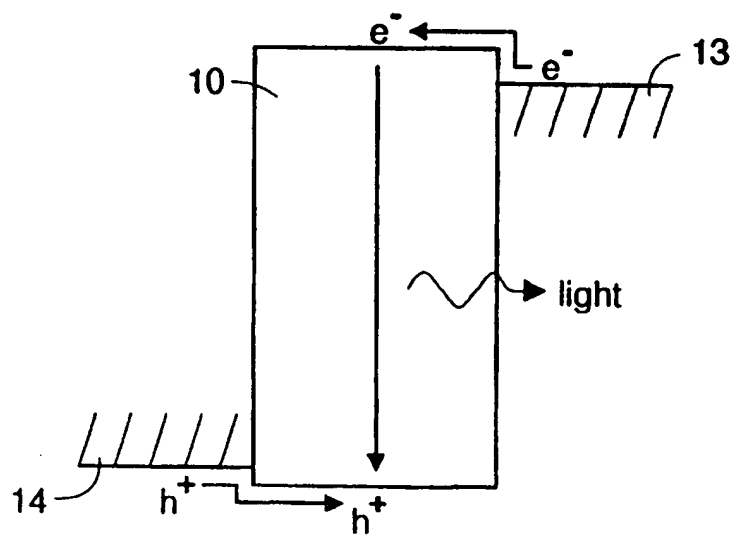
- 1 20. Organic light emitting array or display comprising more than one light
emitting device pursuant to any of the preceding claims.
21. The organic light emitting array or display of claim 20, wherein said
5 substrate is a a Silicon substrate comprising devices and/or circuits
and/or electrical connections.
22. The organic light emitting array or display of claim 21, wherein said
10 devices and/or circuits and/or electrical connections are designed for
driving and controlling at least one of said light emitting devices.
23. The organic light emitting array or display of claim 20, comprising color
15 filters and/or color converters (134; 142) providing for the emission of
light at different wavelengths.
24. The organic light emitting array or display of claim 21, wherein said
light emitting devices are deposited cathode first or anode first onto
said Silicon substrate.

20

25

30

1/16

FIG. 1A
(Prior Art)FIG. 1B
(Prior Art)

2/16

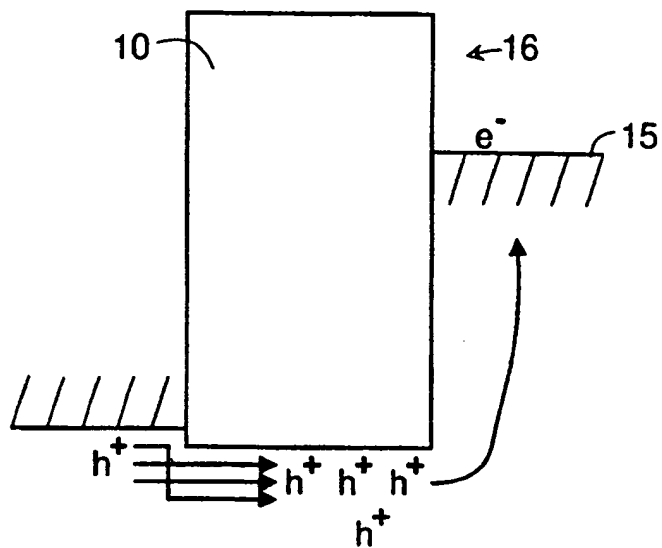


FIG. 2A
(Prior Art)

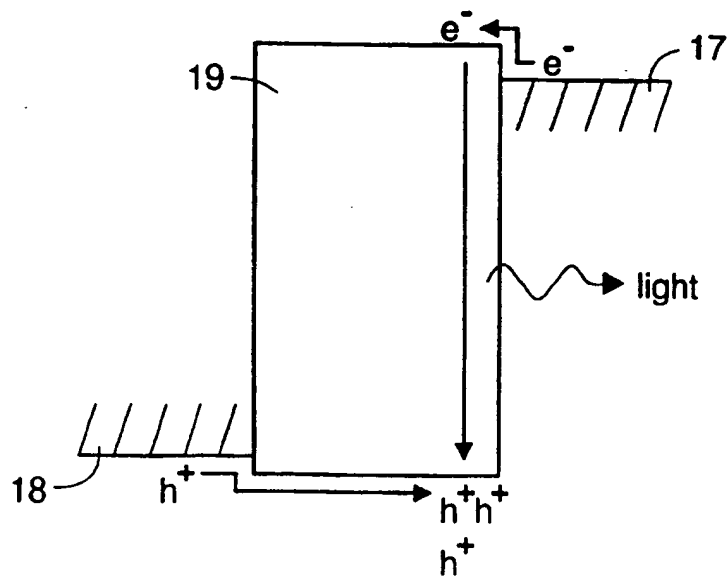


FIG. 2B
(Prior Art)

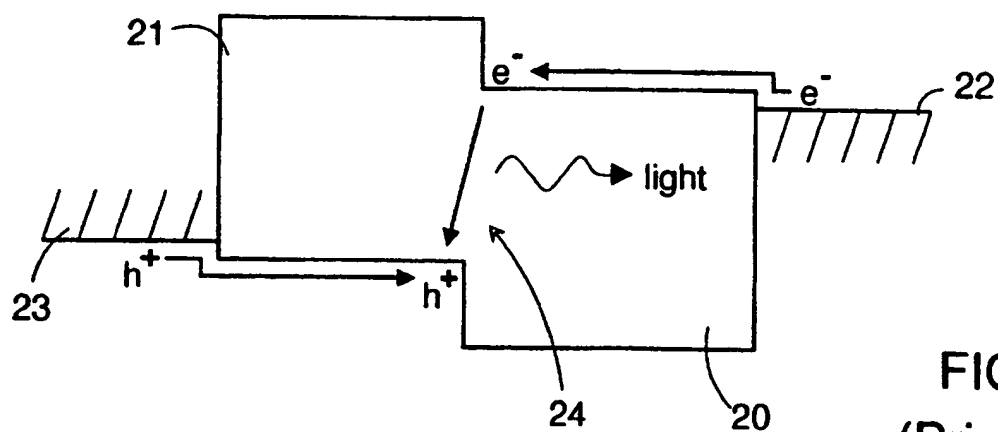


FIG. 3
(Prior Art)

4/16

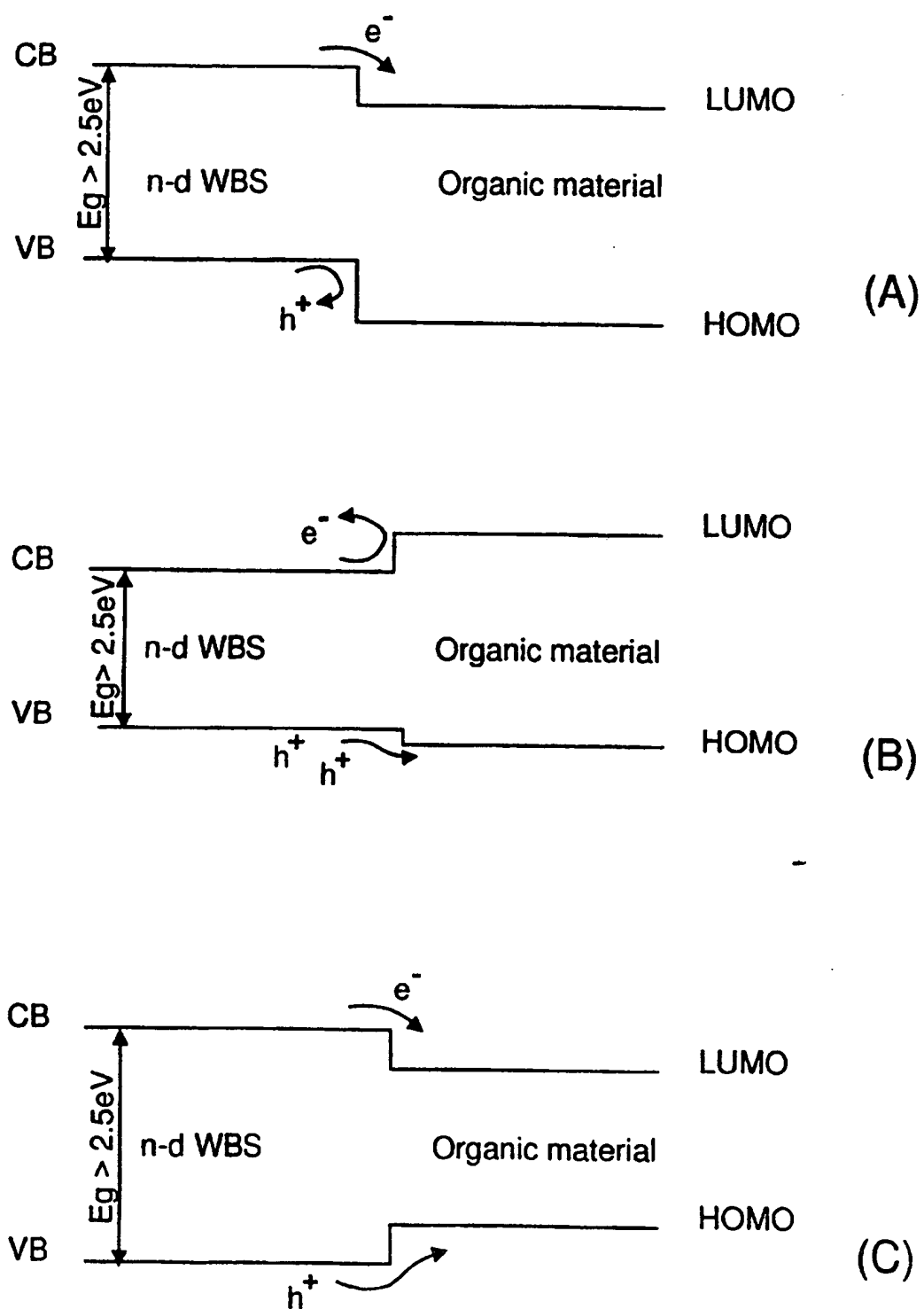


FIG. 4

5/16

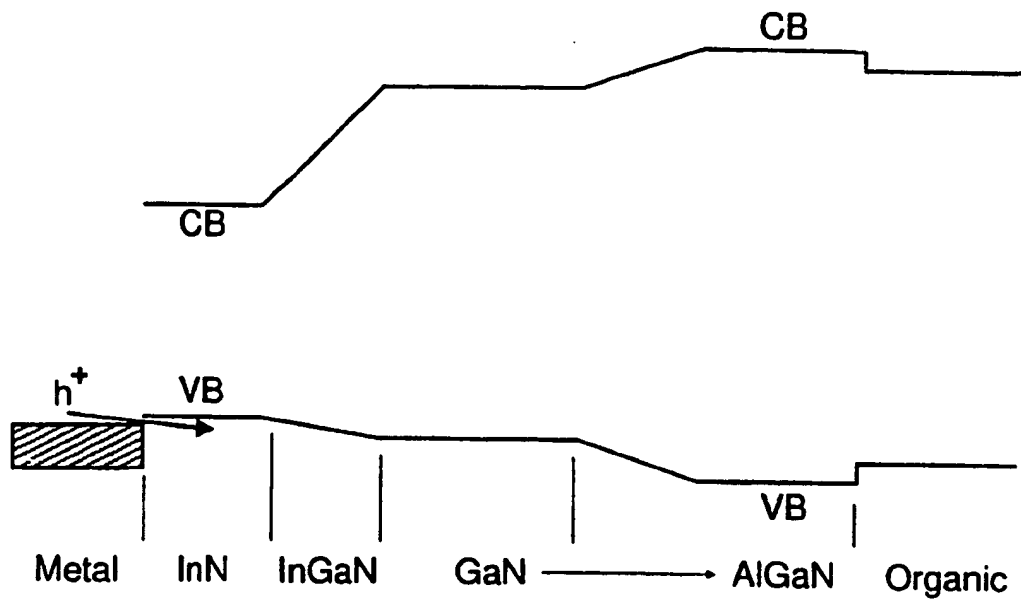


FIG. 5

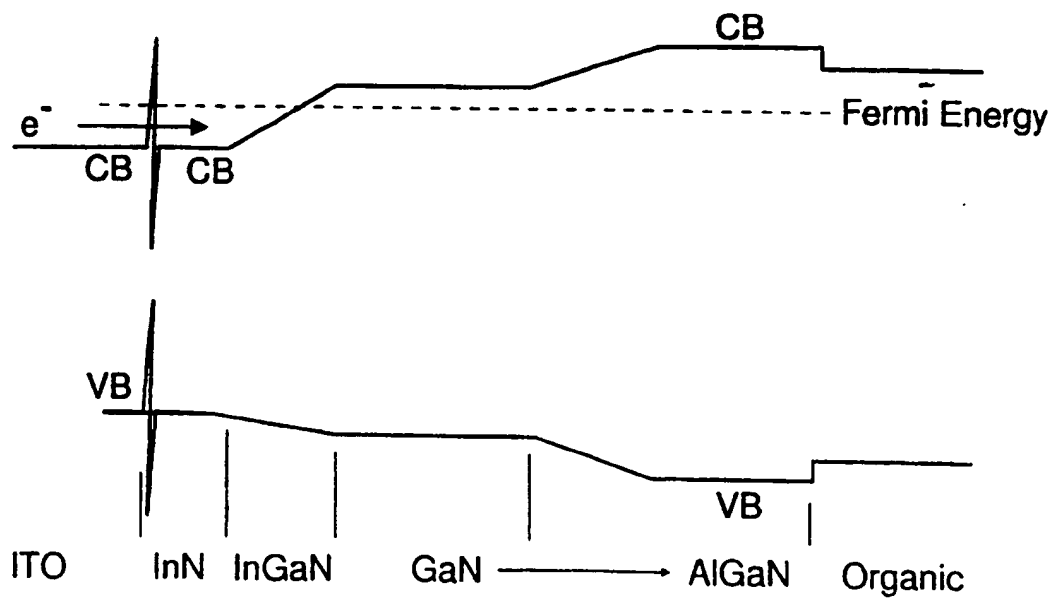


FIG. 6

6/16

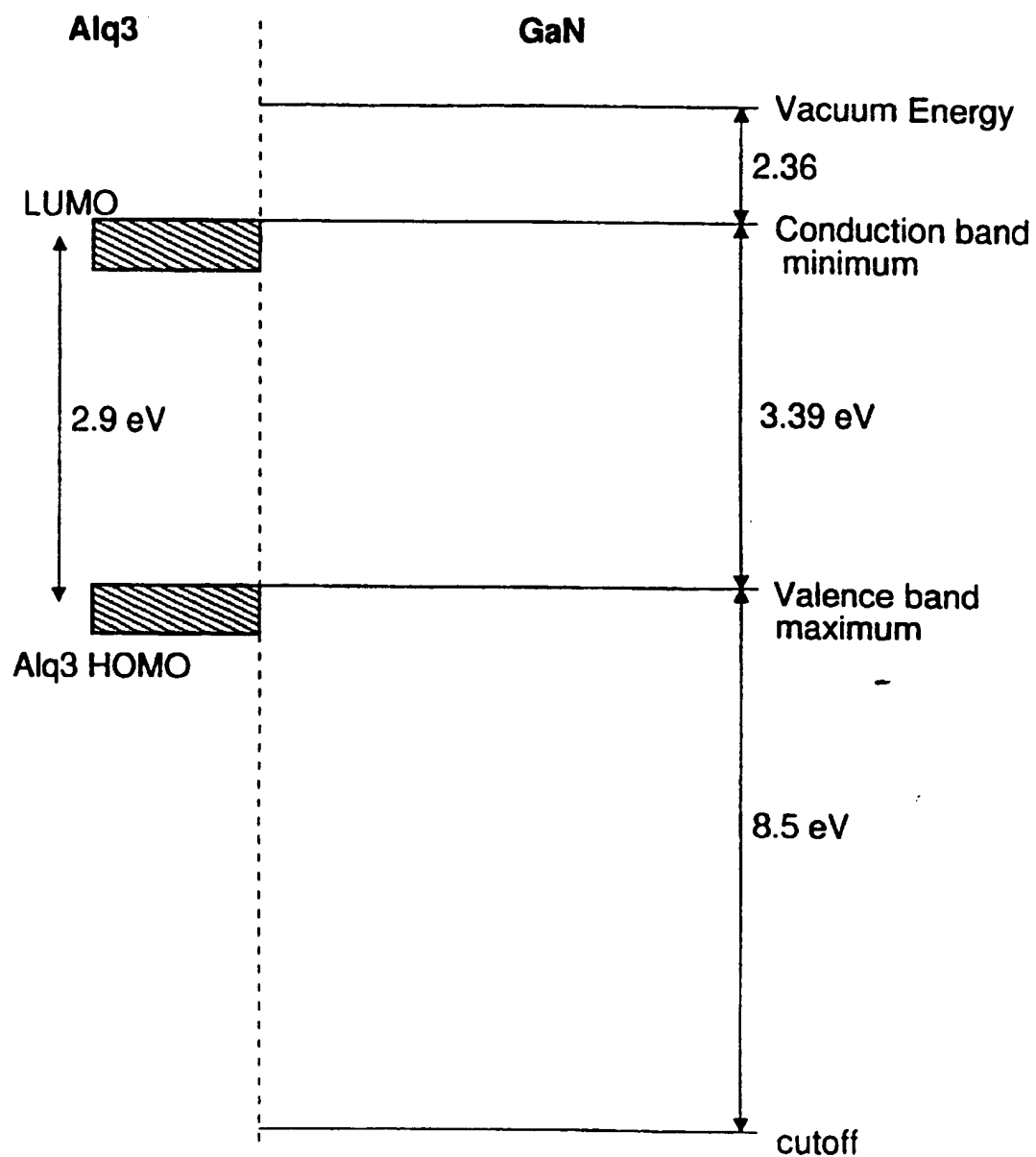
Energy level diagram for
GaN and Alq3

FIG. 7

7/16

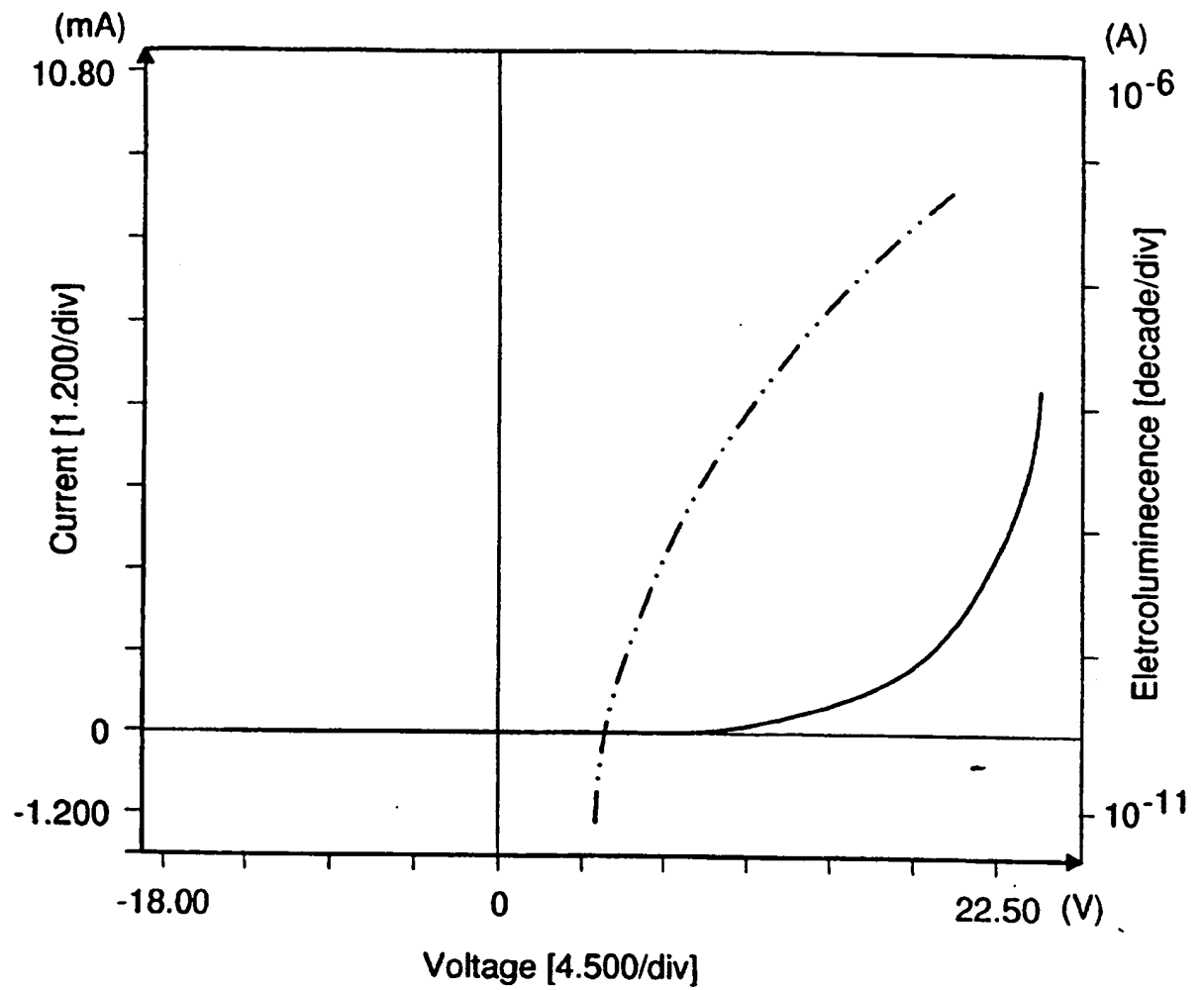


FIG. 8

8/16

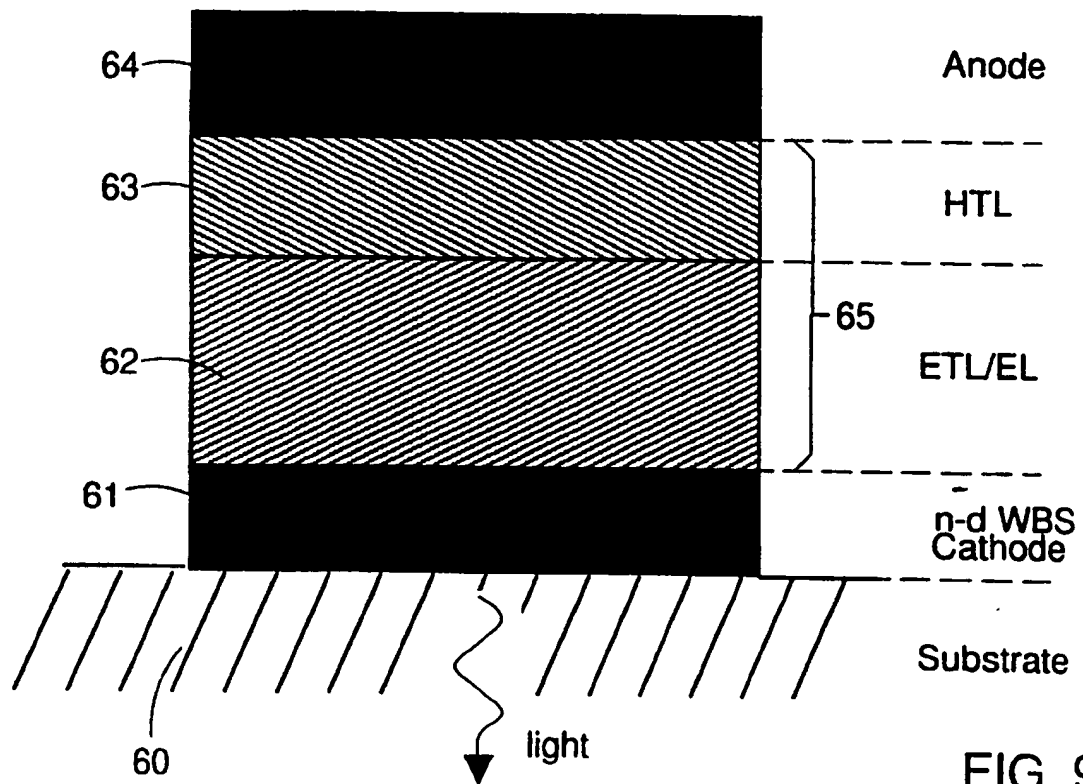


FIG. 9

9/16

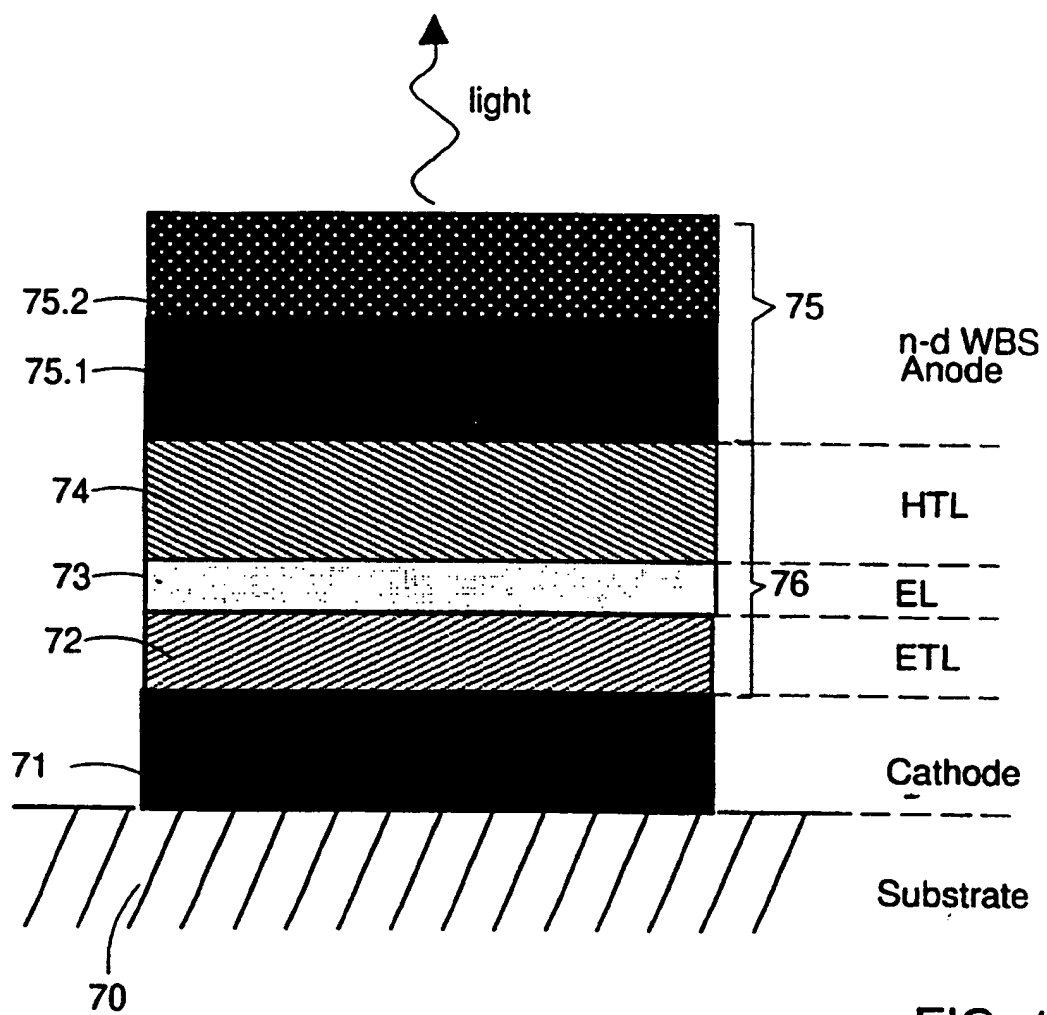


FIG. 10

10/16

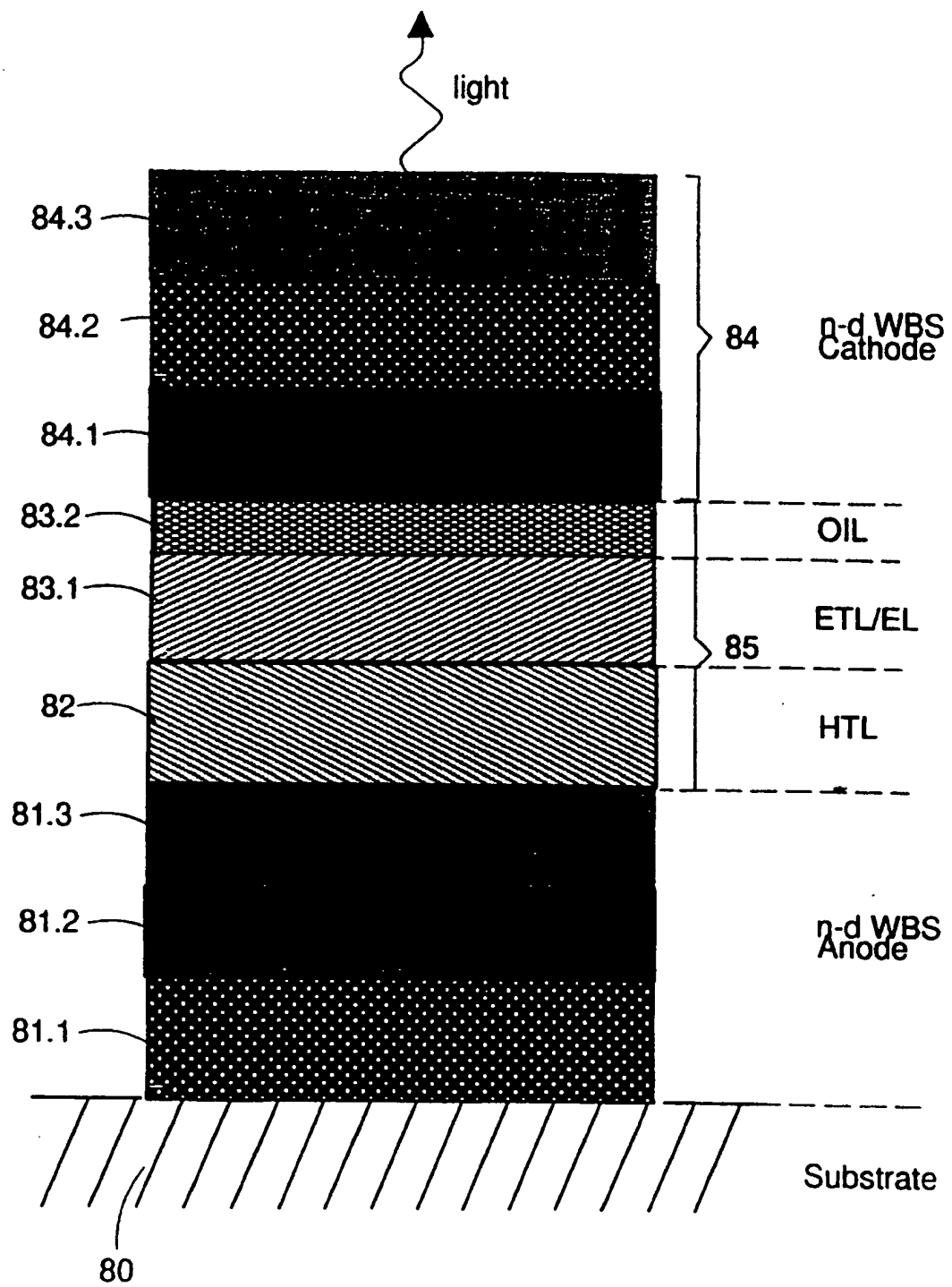


FIG. 11

11/16

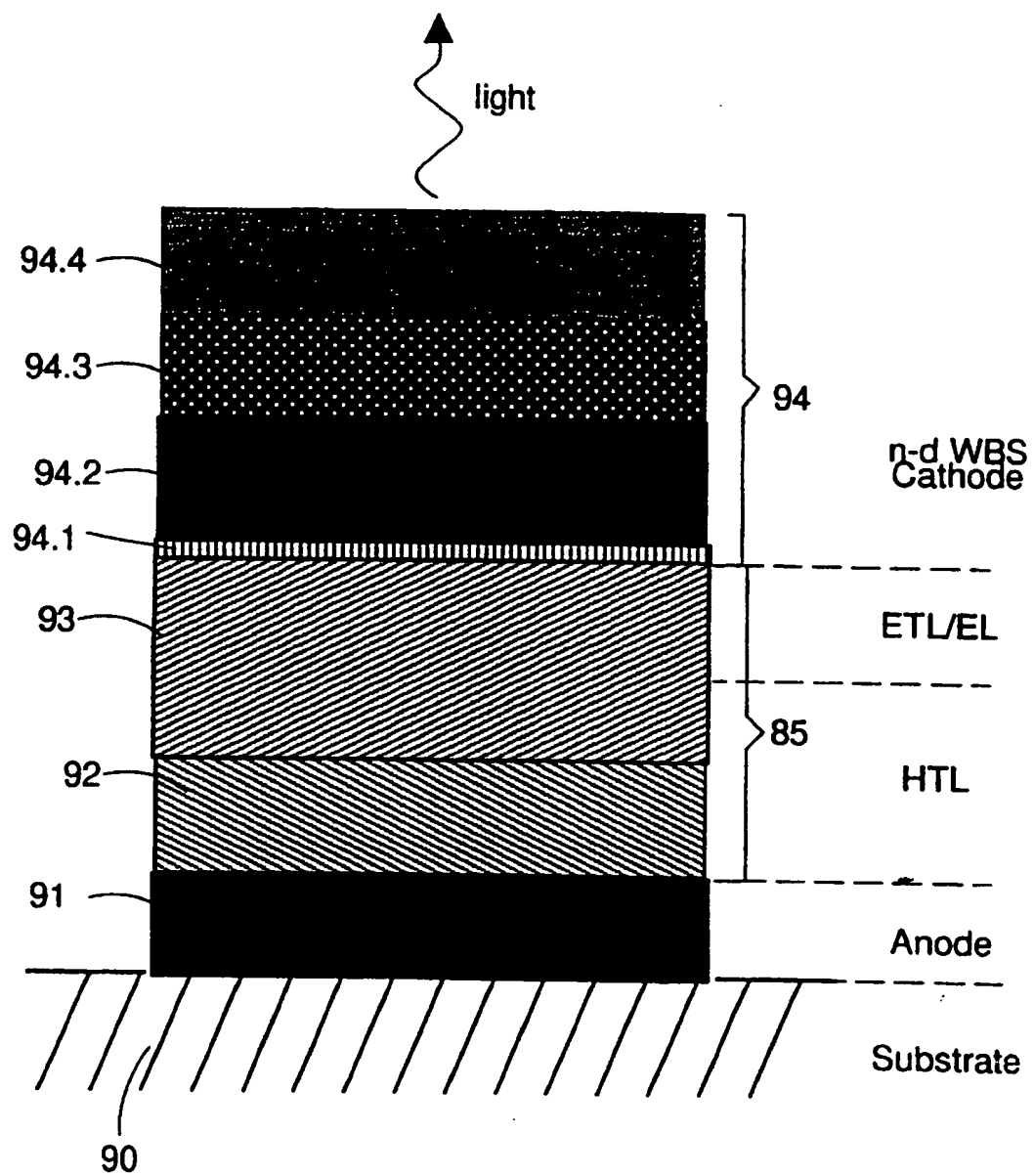


FIG. 12

12/16

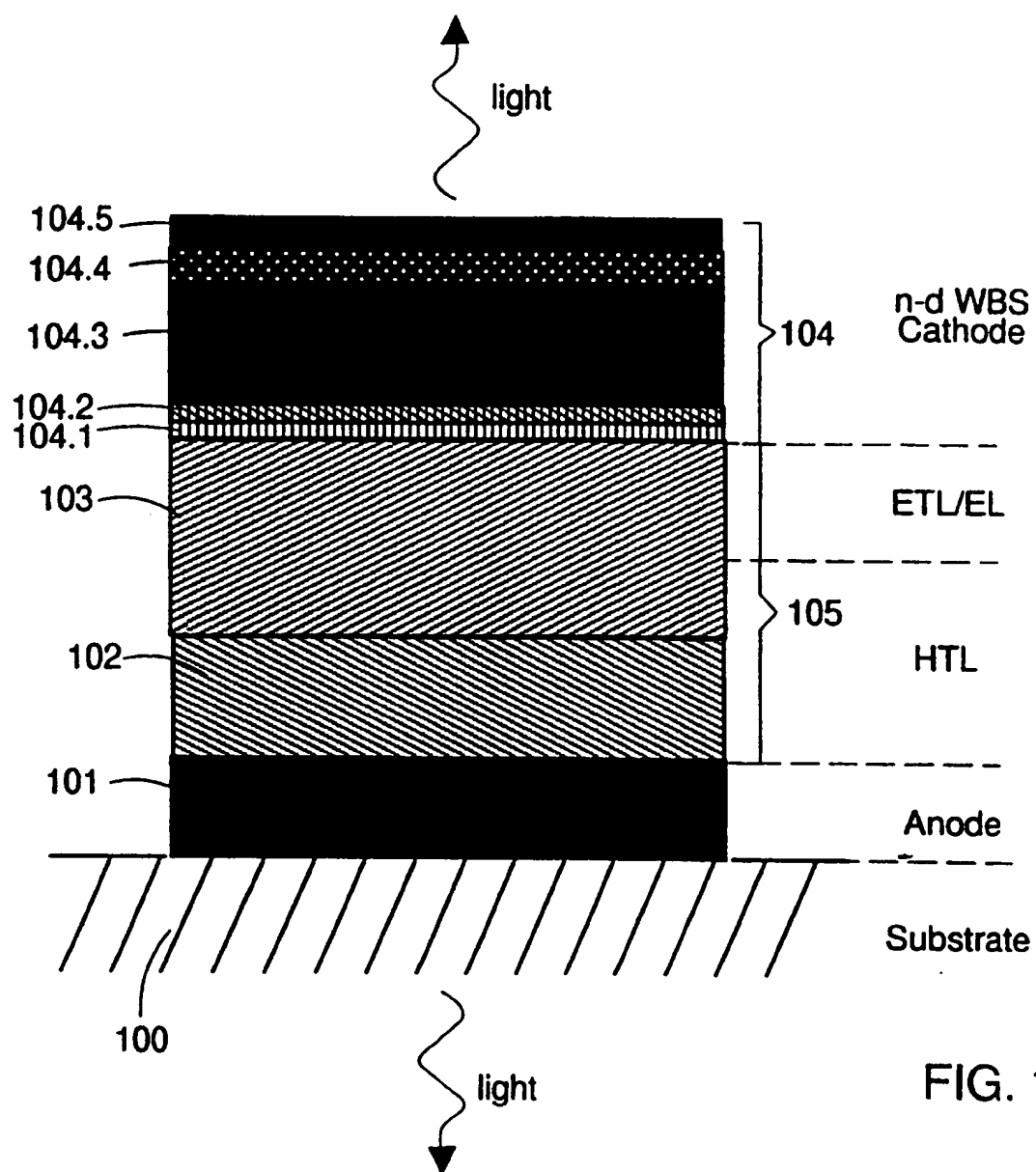


FIG. 13

13/16

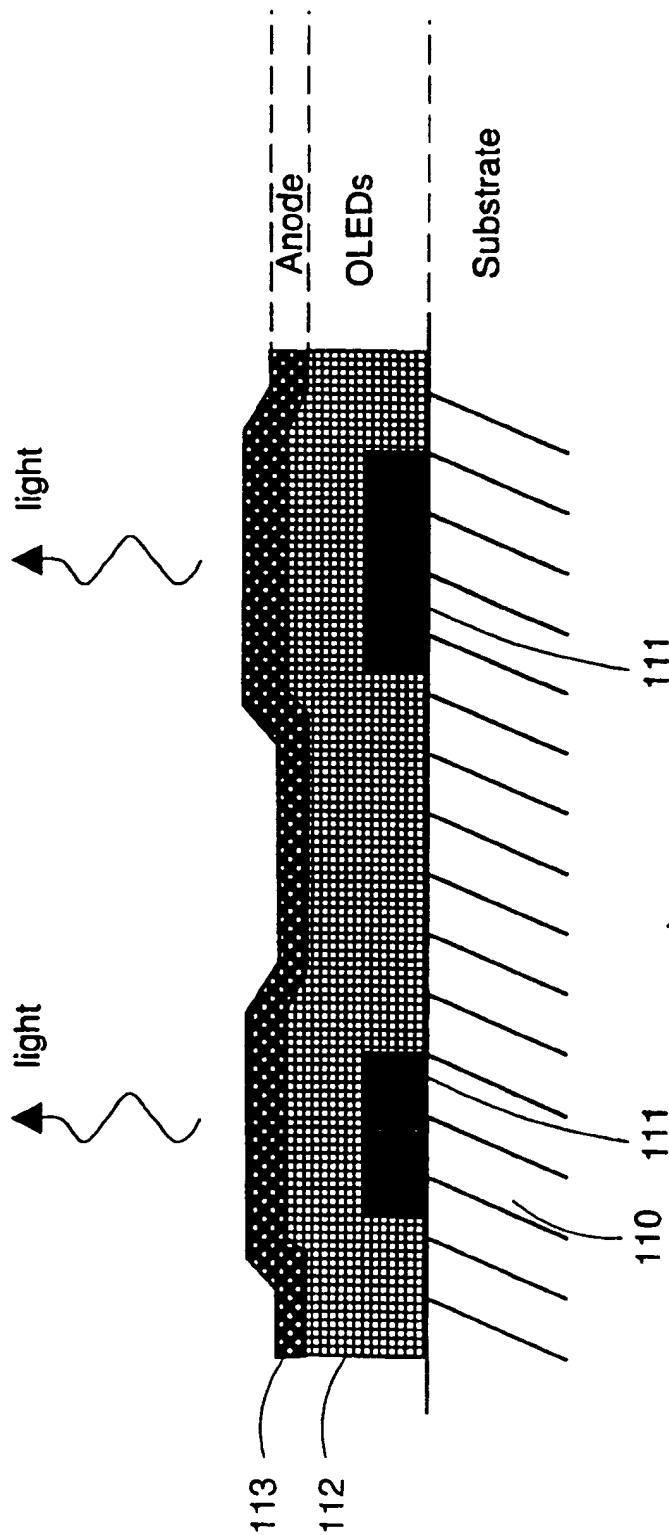


FIG. 14

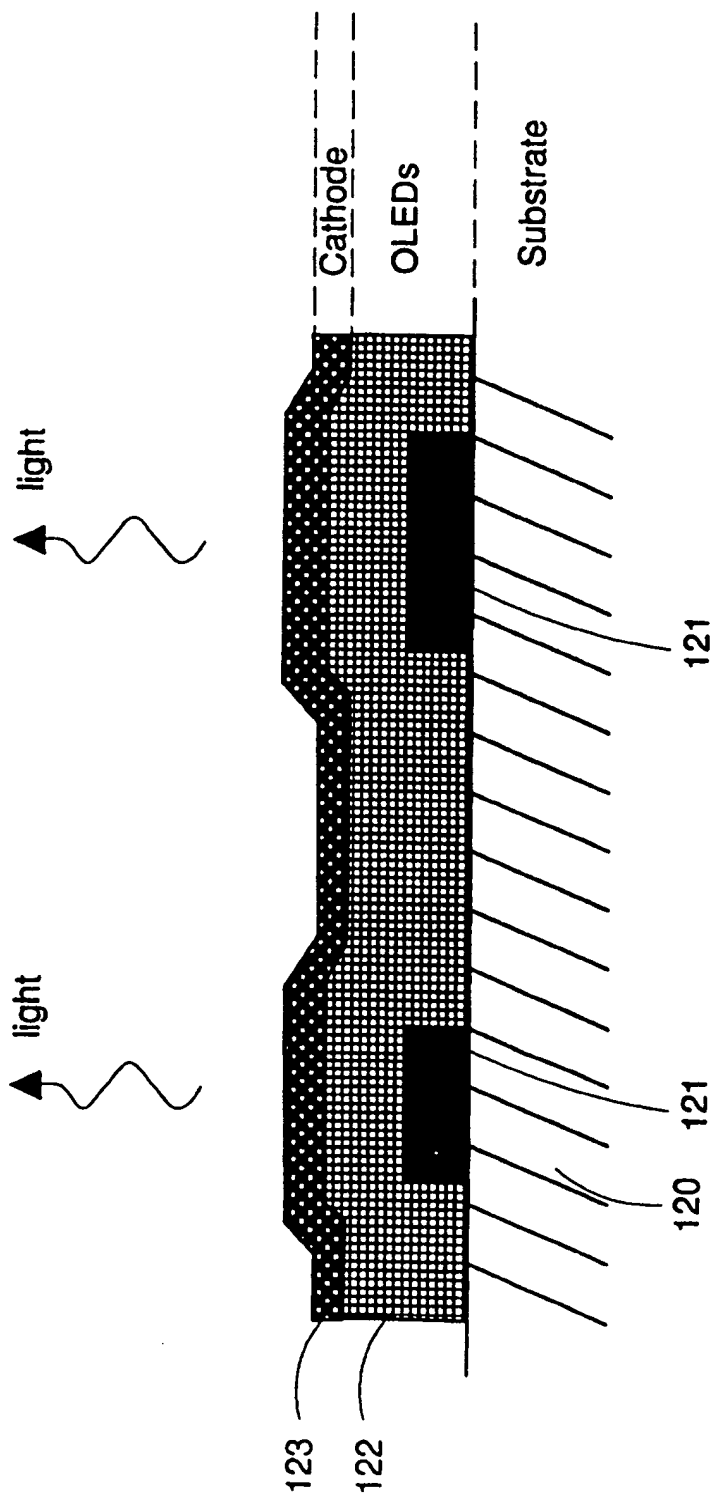


FIG. 15

15/16

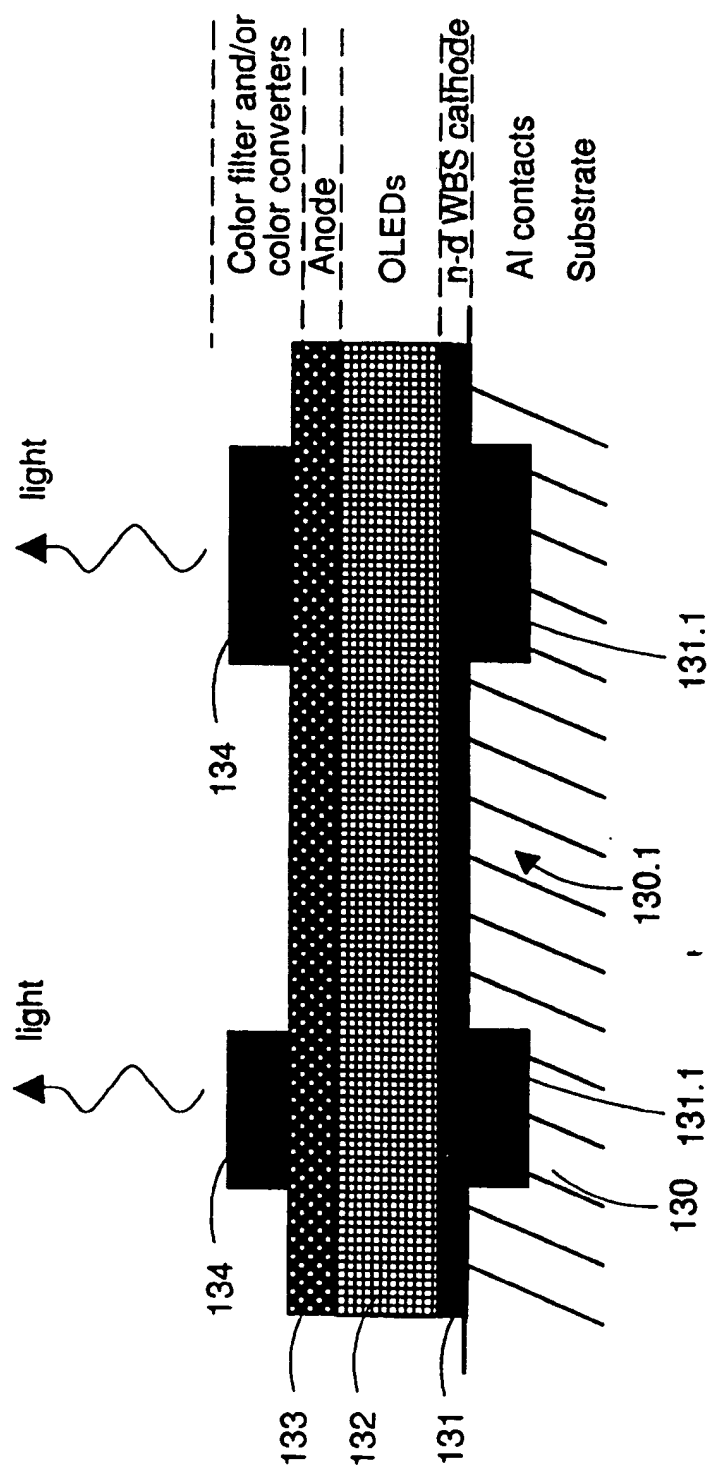


FIG. 16

16/16

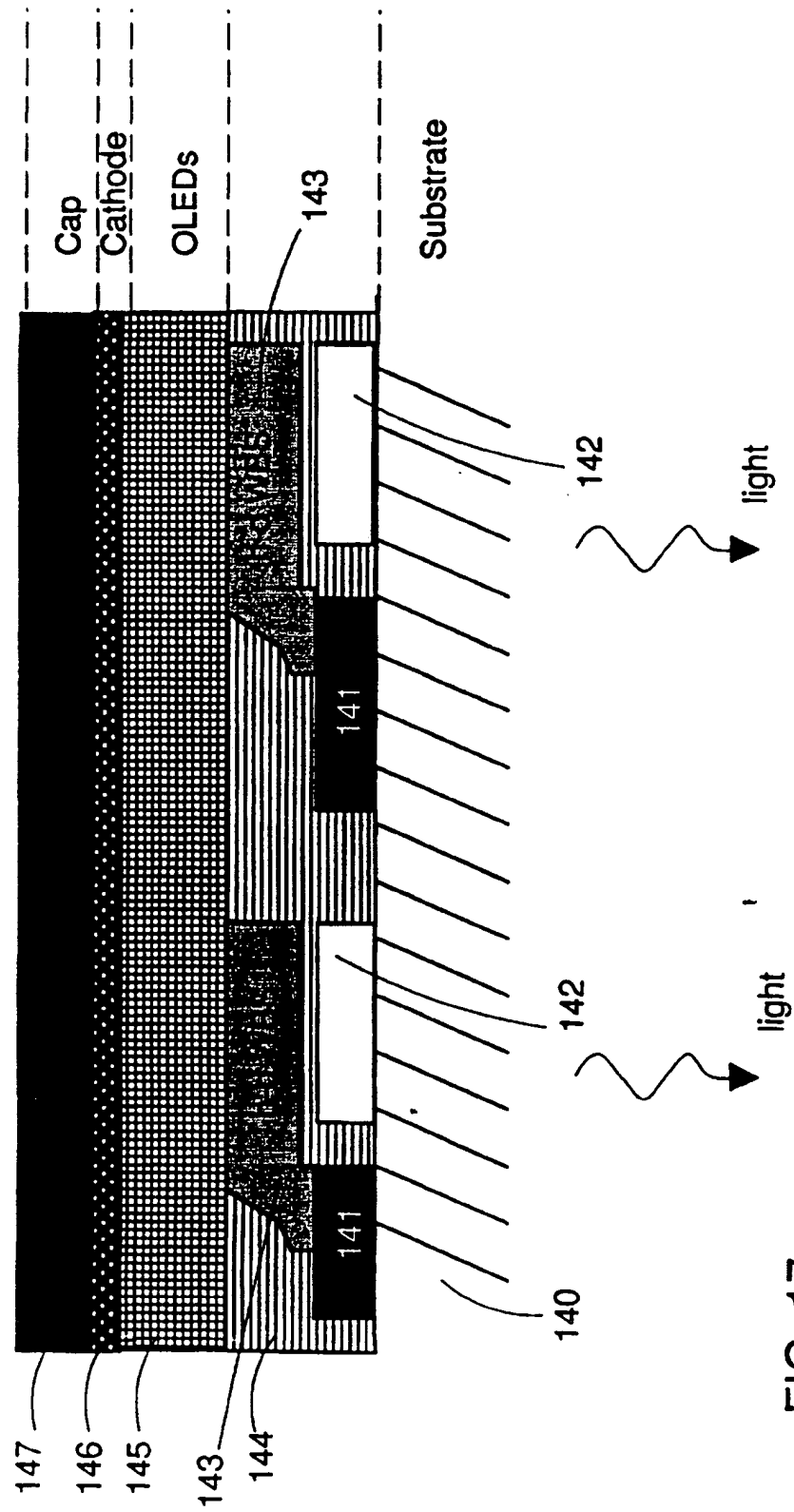


FIG. 17

INTERNATIONAL SEARCH REPORT

Inter: ial Application No

PCT/IB 96/00557

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01L33/00 H01L51/20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 H01L H05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP,A,0 448 268 (TOKYO SHIBAURA ELECTRIC CO) 25 September 1991 see page 2, line 1 - page 6, line 35; figures 1-8	1,3-7, 12,17,19
A	--- JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 12, no. 12, 1 December 1994, pages 2107-2112, XP000493718 KIM H H ET AL: "SILICON COMPATIBLE ORGANIC LIGHT EMITTING DIODE" see the whole document	1,16,20, 21
A	--- PATENT ABSTRACTS OF JAPAN vol. 011, no. 275 (E-537), 5 September 1987 & JP,A,62 076576 (TOSHIBA CORP), 8 April 1987, see abstract	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

A document defining the general state of the art which is not considered to be of particular relevance

E earlier document but published on or after the international filing date

L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

O document referring to an oral disclosure, use, exhibition or other means

P document published prior to the international filing date but later than the priority date claimed

T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

Z document member of the same patent family

Date of the actual completion of the international search

14 February 1997

Date of mailing of the international search report

27.02.97

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

De Laere, A

information on patent family members

PCT/IB 96/00557

Form PCT/ISA/210 (patent family annex) (July 1992)